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MEMOIRS

OF

THE GEOLOGICAL SURVEY OF INDIA.

THE CHARNOCKITE SERIES, A GROUP OF ARCHÆAN HYPERSTHENIC ROCKS IN PENINSULAR INDIA. *By* THOMAS H. HOLLAND, A.R.C.S., F.G.S., *Officiating Superintendent, Geological Survey of India.*

INTRODUCTION.

The older workers on the Geological Survey in South India followed the prevalent theories of the day in considering the Archæan gneisses and schists to be merely sediments in a highly advanced stage of metamorphism; but Mr. R. Bruce Foote[1] has recently expressed an opinion that such a conclusion needs revision, and the task now left us is to determine which of these old gneisses are of igneous origin, and which show evidences of being merely metamorphosed sediments.

The first duty, evidently, is to define and separate from their associates the groups which show, throughout their constituent members, a sufficient similarity of family characters to indicate identity of origin and a genetic relationship one to another. The

[1] "The Geology of the Bellary District." *Mem. Geol. Surv. Ind.*, Vol. XXIV (1895), p. 27.

next duty is to apply to each group or family so defined the tests which are recognised as safe criteria for distinguishing rocks of igneous from rocks of sedimentary origin. The first section of this memoir is therefore devoted to explaining the general features which serve to connect and show the consanguinity of the types grouped together under the name *charnockite series*, whilst the succeeding chapters discuss the question of their origin.

The most abundant and not the least interesting of the old crystalline formations in South India are the great masses of rock whose two leading characteristics are a granulitic structure and the invariable presence of a rhombic pyroxene amongst the constituents. That such rocks as these existed in the Madras Presidency was, so far as I can find, first recognised by Professor Judd, who employed material collected in the Nilgiris to describe the properties of the highly pleochroic, rhombic pyroxene which approaches Vom Rath's amblystegite in composition.[1]

Later, Prof. A. Lacroix,[2] in his memoir "Contributions à l'étude des gneiss à pyroxène et des roches à wernérite" described as *pyroxene-gneisses* a number of specimens which had been collected as long ago as 1819 by Leschenault de la Tour.[3] Some of these rocks resemble the types herein grouped together under the name *charnockite series*.

At the end of 1891, and during the first three months of 1892, I made a tour through the southern districts of the Madras Presidency and then found that these rocks had a very wide distribution in the South of India. They were first found in full variety at St. Thomas' Mount and Pallavaram, 10 miles south of Madras city; from quarries in these localities large quantities of rock have been obtained for building and ornamental purposes in Madras. Subsequently the same rocks were found to make up the mountain masses of the

[1] *Quart. Journ., Geol. Soc.*, Vol. XLI (1885), pp. 371 and 372.

[2] *Bull. de la Soc. Fr. de Min.*, Vol. XII (1889), p. 83, and *Rec. Geol. Surv. Ind.*, Vol. XXIV (1891), p. 157 (translation by Mallet).

[3] In a separate paper I have given an account of M. Leschenault's geological observations in South India, together with the results of an attempt to identify the localities of the specimens described by Lacroix.

Shevaroys, the Nilgiris, the Palnis and the great ridge of high ground forming part of the Western Ghâts, stretching southwards as far as Cape Comorin and reappearing above the sea-level in Ceylon.

In the following year Mr. F. G. Brook-Fox, F.G.S., called my attention to the occurrence of the same rocks in the South Arcot district, and during the succeeding field season Dr. H. Warth made a representative collection of the principal types exposed in that area.

At about the same time Mr. C. S. Middlemiss commenced survey work in the districts of Salem and Coimbatore, and with the assistance of Mr. F. H. Smith has since added several new localities to those previously known.

In the summer of 1897 I was able to devote a month towards the examination of some of the interesting features presented by this group in the immediate neighbourhood of Salem, whilst the following field season was devoted to a systematic survey of the little province of Coorg on the Western Ghâts, where, with the help of Dr. T. L. Walker, some very interesting facts, bearing especially on the geological relations of these rocks to the older gneisses, were discovered.

All the observations above referred to were made after the real nature of the rocks had been discovered by microscopic examination, and although the petrological features of the same areas have frequently been referred to in papers on related subjects published since 1892, no systematic description of the group has hitherto been put on record.

Messrs. F. H. Smith and T. L. Walker have recently found the charnockite series developed over large areas in the districts of Ganjam and Vizagapatam.

PART I.

PETROGRAPHY OF THE SERIES.

CHAPTER I.

PREVIOUS DESCRIPTIONS OF THE SERIES.

Before the establishment of an organised Geological Survey of India various disconnected descriptions of the rocks now included in this group were published by several independent observers in the South of India, such as those by Dr. P. M. Benza,[1] Captain J. Allardyce [2] and Captain J. Ouchterlony.[3]

Benza referred to St. Thomas' Mount and the hills at Pallavaram as composed of "hornblende rock overlying the fundamental rock." Captain Allardyce evidently recognised the similarity between what he called the "primitive trap allied to sienitic granite" of Pallavaram and the rocks forming the principal mass of the Nilgiris (Neilgherrys) and Shevaroys, as well as those forming the Western Ghâts and Ceylon. He speaks of the great abundance of this rock, and asserts that it "cuts off and terminates all other granites". Benza referred to the rocks of the Nilgiris in somewhat similar terms. "The lowest visible rock of the Nilgiris is," he says, "of the primitive unstratified class, including true granite, pegmatite, sienitic granite and hornblende rock; sienitic gneiss and hornblende slate are occasionally seen, but they belong more to the outskirts of the hills" (*loc. cit.*, p. 256). The same author also noticed the smoky and bluish quartz which is so common in the charnockite series

[1] "Notes on the Geology of the Country between Madras and the Neilgherry Hills viâ Bangalore and viâ Salem". *Madras Journ. of Lit. and Sci.*, Vol. IV, pp. 1—27 (1836). "Memoir on the Geology of the Neilgherry and Koondah Mountains". *Ibid.*, Vol. IV, pp. 241—299 (1836).

[2] "On the Granitic Formation and direction of the Primary Mountain chains of South India". *Ibid.*, Vol. IV, pp. 327—335 (1836).

[3] "Geographical and Statistical Memoir of the Neilgherry Mountains. *Ibid.*, Vol. XV, pp. 1—138 (1848).

(p. 257). Captain Ouchterlony in 1848 referred to the mass or nucleus of the mountains as "granite frequently passing into sienite" (*op. cit.*, p. 2). He draws a distinction between the "granite", "sienite" and "hornblende rock" of the Nilgiris on the one hand, and the "beds of gneiss" met with in the plains on the other.

With the systematic mapping which was commenced by the officers of the Geological Survey of India in 1857, a large mass of information was accumulated concerning the distribution of the charnockite series, as well as other formations in South India. The macroscopic and field characters of the rocks have been clearly described in the reports of the work done by H. F. Blanford, C. Æ. Oldham, W. King, R. B. Foote and P. Lake, most of which have been published in the *Memoirs* and *Records* of the department.[1]

As at the time of the issue of these publications provision had not been made in the department for microscopic examination of the rocks, the wide prevalence of the pyroxenes, and especially of the rhombic forms, was not noticed, the dark mineral in the rocks being generally referred to hornblende, which is also an abundant constituent. Following also the theories then prevalent as to the nature of the Archæan crystalline rocks, most of the authors who described the geological features of Madras regarded the gneissose and the banded structures as evidence in favour of considering the crystalline rocks to be the results of the metamorphism of sediments. But we now know that neither the gneissose structure, nor the banding due to differences in mineral composition of the "beds," differs essentially from the phenomena presented by some rocks whose eruptive origin is established beyond dispute. In the light of this modification of old views concerning the gneisses it becomes necessary to separately re-examine each group and record the evidences bearing on its origin.

[1] See Manual, Geol. of India, 2nd Ed., pp. 36—39.

CHAPTER II.

DISTINGUISHING FEATURES OF THE SERIES.

Consanguinity of the members.

The unaltered varieties of this series present such a remarkable and unmistakeable individuality in macroscopic characters that they are easily distinguished in the field from the other crystalline rocks with which they are associated. On account of the striking nature of the characters which give the different varieties of the group such an unmistakeable family likeness—"consanguinity," to use Iddings' expressive term—the peculiar characters distinguishing one variety from another are so well masked, that the forms containing sufficient free quartz and siliceous minerals to raise the silica percentage to that of the granites might very easily be confused with the varieties whose mineral composition agrees with that of typical norites.

Macroscopic characters.

The leading features in hand-specimen of the common, that is the unaltered and medium-grained types, are the blue-grey to dark-green colour, the subconchoidal fracture, and the absolutely fresh condition of the rock. Examination of the coarse-grained types with the naked eye, or of the fine-grained ones with the lens, shows that quartz when present is almost invariably blue in colour, like that of the well-known Rumburg granite (granitite); the felspars present a similar blue or blue-grey colour, and, but for their cleavage faces, might easily be mistaken for quartz. These minerals, therefore, which generally give the lighter colours to our ordinary acid rocks, are almost as dark in the Madras "pyroxene-granulites" as the associated ferromagnesian silicates; and this circumstance, together with the fact that opaque iron-ores are equally abundant in all types, are the principal causes which give the acid and basic members of the series such a similarity of appearance in hand-specimen.

17. Microscopic examination shows that the similarities in macroscopic characters are only the outward and visible signs of a constancy in structure and mineral composition. The one constant feature in *structure* is the *even-grained, granulitic* (panidiomorphic) character of the constituents. The constant feature in *composition* is the presence of *rhombic pyroxene*, which is generally highly pleochroic, approaching hypersthene, or in some cases amblystegite, in composition.

Microscopic characters.

The above two characters are constant in what I regard as the unaltered forms of the rocks. But in those which show a clearly defined gneissose structure by linear arrangement of the minerals signs of dynamo-metamorphism are sometimes displayed, and *pink garnets* almost invariably appear. I have said signs of dynamo-metamorphism are *sometimes* displayed, because, although nearly all varieties show a linear arrangement of the constituent minerals, the frequent absence of all signs of crushing shows that in some instances the crystals were arranged with their long axes at right angles to the direction of maximum pressure before consolidation. Whether this unequally distributed pressure was due to actual lateral compression, or to fluidal movements analogous to that which has frequently been recorded in dykes, it is impossible to determine, and, as far as concerns our conclusions as to the origin of these rocks, is of little consequence.

Characteristic constituents.

Besides *hypersthene*, which is an invariable constituent, and *garnet*, which is extremely common, the following minerals are frequently found in members of this series:—

Quartz.—Blue, grey, or greenish, often with innumerable acicular inclusions Also intergrown with felspar to produce the so-called "quartz de corros ion" of the French petrographers.

Potash felspar.—Often as microcline and frequently microperthitic.

Plagioclase.—In the basic types generally approaches labradorite or labradorite-andesine in composition.

Augite.—A pale green, feebly pleochroic variety, frequently exhibiting lamellar twinning.[1]

Hornblende.—A brown-green, highly pleochroic variety with an extinction angle of about 11°.

Biotite.—Very variable in quantity, appears in most exposures.

Graphite.—Evenly distributed like the other constituents, though smaller in quantity, and found in two exposures only.

Zircon and *apatite* are nearly always present in small quantities.

Iron-ores, *magnetite* and *titanoferrite* are invariably present and generally in large quantities; *pyrite* and *pyrrhotite* are often developed near the junctions of two distinct varieties.

Except in one aberrant form presenting several peculiar and unusual features *sphene is absent.* The occurrence of the titanic acid in the form of ilmenite instead of as sphene is a feature which distinguishes these rocks from some associated gneisses, and also separates the normal from the altered forms.

[1] Lacroix (Rec. Geol. Surv., India, XXIV, 173) mentions the occurrence, in the "pyroxene gneisses" of Salem, of a monoclinic pyroxene with a pleochroism similar to that of hypersthene, namely, c = sea green, b = bright pink and a = yellowish green, with an extinction angle of 45° on the clinopinacoid (010). It may be stated at once that, although I have examined hundreds of cases from the Salem district and from all parts of the Madras Presidency, I have never yet found a pyroxene in these rocks giving the pleochroism of hypersthene without at the same time, when definite cleavage lines are exhibited, showing a straight extinction. At the same time the commonest of all the types of these rocks is one in which both pyroxenes occur together; the one strikingly pleochroic and unmistakeably rhombic in its crystallization, whilst the other is very feebly pleochroic in greens only, giving wide extinction angles.

The green colour of the hypersthene, however, so nearly resembles that of the monoclinic pyroxene, that without moving the polariser the similarity of refractive index and crystal habit might, in a hasty examination, result in a confusion of the two forms. As the rocks described by Lacroix so remarkably resemble in other respects those which I include in the series now under description, I have very carefully searched every specimen in the extensive collection made by my colleagues and myself, and have to confess my inability to discover a single instance of such a pleochroic monoclinic pyroxene.

Corundum, sillimanite, green spinel (hercynite or pleonaste) and rutile characterise the contact products in inclusions which are regarded as xenoliths and not true members of the series. Scapolite, sphene and lime-garnet occur where these rocks are associated with crystalline limestones and are considered to be either primary or secondary endogenous products of contact metamorphism.

CHAPTER III.

NOMENCLATURE.

So far as we know, the rocks described in this paper are of Archæan age and have as their nearest foreign equivalents the rocks known to the German petrographers as "pyroxene granulites" and to the French as "pyroxene gneisses". Although their predominating features are those which characterise the "pyroxene granulites," they also show points of resemblance to certain varieties of the "norites" of Scandinavia and sometimes to the "anorthosites" of Canada, besides possessing peculiarities of their own. But whether the rocks now under consideration ultimately prove to be the equivalents of anyone or all of the above-mentioned foreign groups is at present difficult to determine: the important point for us is that within the limits of Peninsular India they form a distinct and very large subdivision of our old crystalline rocks, possess a very well defined series of characters and present a constant relation to the older gneisses; in fact, *they constitute a distinct petrographical province,* which we propose to distinguish by a special name in our literature, and, when possible, by a special colour on our maps.

The name *charnockite series,* which we now commonly employ for these rocks in India, expresses the fact that we group together in one petrographical province a number of lithical types genetically related to charnockite (*vide infra,* p. 134) and to one another. Within this petrographical province there are petrical and lithical forms which vary from the acid charnockite to the ultra-basic pyroxenite; but any one who has studied the group in the field would readily recognise the consanguinity of the different members, and indeed would often find it difficult, without the aid of the specific gravity balance or the microscope, to distinguish an acid from a basic variety.

Our name charnockite series thus enables us to bring together a set of genetic relatives, which, by the ordinary systems of

petrographical classification would be separated from one another; and at the same time we avoid the vexed questions which the terms "pyroxene granulite" and "pyroxene gneiss" would naturally provoke. We are far more certain that the different members of the charnockite series are related to one another than we are that they are related to the European "pyroxene granulites," and for the purpose of mapping it is safer, at least as a temporary measure, to adopt a local term, such as a stratigraphist, for instance, would do under like difficulties.

Besides the advantages which a new and local term offers from a purely survey point of view, there are certain theoretical objections to the use of the alternative foreign terms for rocks which are probably, though not certainly, the equivalents of our charnockite series. Against the use of the term "pyroxene granulite" for instance, there is (1) the fact that the rocks herein referred to are not all granulitic in structure, and (2) the specific meaning attached to the word "granulite" by the French petrographers, who apply it to an eruptive muscovite-granite poor in mica and approaching the so-called aplites in composition.[1] Against the use of the term "pyroxene-gneiss" there is (1) the fact that the rocks under consideration are not always "gneissose", (2) the circumstance that to many this term would imply a definite geological age and origin which are not proved, and (3) there are many gneisses in India containing pyroxene which are not genetic relatives of the charnockite series, and should not therefore be grouped with them.

Classification by petrographical provinces.

Unfortunately our modern systems of nomenclature make no provision for indicating petrographical provinces, because no system of rock-classification makes any pretence towards an expression of genetic relationship between the so-called families. From the purely petrological and hand-specimen point of view, it may be convenient to adopt Rosenbusch's system of dividing rocks into three classes according to the purely accidental circumstances attending their

[1] Michel-Lévy. *Bull. de la soc. geol.*, 3rd series, Vol. II (1874), p. 180.

consolidation; but as such a system must always separate rocks that are magma relatives, and bring together others that have no genetic relationship, it falls short of the requirements of the geological surveyor. For the wider problems of geology it is necessary that we should know how to subordinate the accidental differences to the general family likenesses between rocks, to group together, in fact, those which have been produced by the same geological effort, and which form a geological unit. In other words, the geological surveyor is more concerned with the delimitations of the petrographical provinces represented within his country than with the mere cataloguing of lithical varieties.[1]

Whilst, therefore, we group together, and map as one formation, a number of diverse varieties of rocks (which are true compatriots within this petrographical province) under the name *charnockite series*, the various constituents of this formation may be distinguished from one another by the ordinary names used for equivalent mineralogical aggregates. As we believe the charnockite series to be igneous in origin and to present intrusive relations to their older neighbours, the terms used for the rock varieties within the group are those commonly used for mineralogically similar igneous rocks. Thus the types which are composed essentially of hypersthene and plagioclase are *norites*, and, according to the ferromagnesian silicate associated with the rhombic pyroxene, we may have augite-norites, hornblende-norites, or mica-norites. The acid form, composed of quartz, microcline, hypersthene and accessory iron-ores, is strictly a *hypersthene-granite or charnockite*, and the non-felspathic forms, composed almost wholly of pyroxenes, are *pyroxenites*.[2]

[1] Prof. Judd was perhaps the first to show by a ground-work of accurately determined petrological and geological data that there is a recognisable set of family characteristics (*consanguinity*, Iddings; *Blutverwandschaft*, Brogger) presented by igneous rocks which, within a limited geographical area, have been formed at a definite geological period, and he expressed these facts by considering such rocks to be members of a *petrographical province*. *Quart. Journ. Geol. Soc.*, Vol. XLII (1886), p. 54.

[2] The term pyroxenite has been used in several totally distinct and unrelated senses, but is now more generally used for eruptive pyroxene rocks.

So too with the structures: the charnockite series occur in dykes and in bosses ; they show basic schlieren, acid contemporaneous veins, primary breccia and other structures peculiar to igneous rock masses, and include foreign bodies (xenoliths).

The name charnockite limited to this province.

But unless a similar formation found in another country, can be proved to be a genetic relation of the typical exposures described in this paper, it is hoped that the name charnockite will never be used outside India. The name is applied to a definite member of a very definite petrographical province now exposed in India, and unless outsiders give it a wider application than that now proposed the terms charnockite and charnockite series need never become a burden to petrographical nomenclature. Charnockite is a convenient name for a quartz-felspar-hypersthene-iron-ore rock in the charnockite series, and not a name for *any* hypersthene-granite occurring in other petrographical provinces. The much-complained-of burdens of petrographical nomenclature are not due to the creation of specific names for local types, but to irresponsible and unwarranted extension of such names to include unrelated members of different and widely separated petrographical provinces, in which the accidents of differentiation and segregative consolidation may have produced by chance similar mineral aggregates.

The charnockite series belong to a very old petrographical province, so old that we have no present reason for separating them from the Archæan "group;" but still young enough to show their intrusive relations to older Archæan formations. During the great lapse of time since the production of the very old geological formations—whether sedimentary or eruptive—secondary changes have tended to remove many of the primary peculiarities of rocks, and have induced the development of a resemblance between genetically distinct types; so that there is always a danger of including unrelated formations when delineating the boundaries and distinctive characters of a very ancient petrographical province. It is possible, therefore, that we may be including under the name "charnockite series"

hypersthene-bearing rocks derived from more than one magma, though all of very great antiquity. That, however, is a difficulty which the stratigraphist has to face also in attempting to compare the chronological values of different "epochs." Still, as long as we keep in view several points of similarity between isolated exposures of the charnockite series, the danger of including too much is partially insured against. As a set-off against this danger, there is a strong probability that the magmas tapped in earlier geological periods were larger than those which gave rise to eruptions after the earth's crust had advanced in physical differentiation.

CHAPTER IV.

DESCRIPTION OF THE CHIEF TYPES.

As already stated, the members of the charnockite series vary from acid types, having the mineralogical and chemical composition of granites, to ultra-basic forms or pyroxenites. For convenience of description, however, they may be divided into four groups which are not sharply marked off from one another :—

(1) *Acid division*, represented by *charnockite*, a hypersthene-granite having a constant specific gravity of 2·67 and silica percentage of about 75. The type-mass forms the central portion of the hill near St. Thomas' Mount (fig. 1). The type-mass is cut through by contemporaneous veins of coarse *quartz-felspar* rock. The garnetiferous forms resemble *leptynites* in composition.

(2) *Intermediate* varieties are by far the most abundant and are characterised by an apparently composite structure, *all* the minerals of the series being frequently found in one hand-specimen with a tendency for the coloured minerals to gather into groups. The average specific gravity is 2·77, with a silica percentage of about 64. Acid contemporaneous veins and basic fine-grained *schlieren* are common. The Shevaroy mass is a typical exposure.

(3) *Basic* forms, mineralogically equivalent to the *norites* and composed of pyroxene (hypersthene and augite), plagioclase and iron-ores, often with hornblende. The type-mass forms the flanks of the hill near St. Thomas' Mount (fig. 1). Specific gravity, 3·03 and silica percentage, 50 to 52. Garnetiferous forms are common near the outskirts of mountain masses, and form large, lenticular bodies in the older gneisses and schists. Garnetiferous as well as non-garnetiferous varieties in Coorg form dykes having chilled selvages.

(4) *Ultra-basic* forms, or pyroxenites, composed of hypersthene, augite, hornblende, sometimes with olivine, green spinel and magnetite. The hypersthenes are sometimes porphyritic, but more generally are perfectly granulitic. Specific gravity, 3·37; silica percentage, 47 to 50. Amphibolization of the pyroxene sometimes results in an almost complete change to hornblende.

These four divisions are described in order below:—

(1) ACID DIVISION.

Charnockite.

Discovery of charnockite.

In October 1892, the Director of the Geological Survey of India announced in his tri-monthly notes, the occurrence in South India of a rock composed of hypersthene, microcline, quartz and accessory iron-ores, referring to it as a hypersthene-granite.[1] As at that time little more was known than the mere occurrence at Pallavaram of a mass of this rock, no further details were published until after my second visit to Madras in September 1893. It was then found that the hypersthene-granite formed large masses associated with granulitic rocks, having the mineral composition of norite (*infra*, p. 153). At about the same time the tombstone of Job Charnock, the founder of Calcutta, was discovered by the Rev. H. B. Hyde in St. John's Churchyard, Calcutta, and when it was found that the tombstone was made of the same hypersthene-granite (which was at the time thought to be a new type of rock), the name *charnockite* was suggested for it in honour of the man who was the unconscious means of bringing the first specimen of this interesting rock to the city which ultimately became the capital of India.[2]

In the same year (1893) Prof. J. H. L. Vogt published the first instalment of a series of papers on the "Bildung von Erzlagers-

[1] *Rec. Geol. Surv. Ind.*, Vol. XXV (1892), p. 190.

[2] *Journ. As. Soc. Beng.*, Vol. LXII (1893), p. 162. Job Charnock died in 1693, and the tombstone was erected two years later.

tätten durch Differentiation-processe in basischen Eruptivmagmata," and referred to the occurrence of a series of rocks at Ekersund in south-west Norway, which appear to strongly resemble those of Pallavaram. The three principal types represented at Ekersund are, according to Vogt, (1) labradorite rocks, resembling apparently the anorthosites of Canada, (2) norites rich in hypersthene and biotite; and (3) a granite composed largely of potash-felspar and quartz with a rhombic pyroxene approaching bronzite in composition, iron-ores in considerable quantities, and a small proportion of an acid plagioclase.[1] Such a description applies exactly to the rock which is known to us in South India as charnockite. But the resemblance of this special type of rock to our charnockite becomes doubly interesting on account of the similarity between the associates in both localities. Although the norites and labradorite rocks differ from the granite so widely in silica percentage, the whole group, according to Vogt, belongs to one petrographical province in which all the members are characterised by the presence of a rhombic pyroxene, and the rocks show an unmistakeable consanguinity (*Blutverwandschaft*) which leaves little doubt as to their derivation from an originally common magma basin. Almost the same words were used in referring to the relatives of charnockite as they are displayed in the neighbourhood of Pallavaram. As remarked in a previous paragraph, the macroscopic characters of the various types so strikingly display the common family characters of the group, that the differences which serve to distinguish the varieties are often remarkably masked.

Norwegian granite with rhombic pyroxene.

At about the same time, therefore, and independently, Vogt discovered in south-west Norway a granite resembling charnockite both in its own composition and in the characters of its associates. Vogt apparently (as well as myself) was under the impression that rhombic pyroxene had not previously been recognised in a granite. I am indebted to Professor Zirkel, however, for calling my attention to the fact that Törnebohm found a rhombic pyroxene to be a constituent of a granite in the neighbourhood of Roxen-See and

[1] Zeitschr. für prakt. Geol., 1893, p. 4.

Ingelsbye in Sweden, whilst Rosenbuch referred to the occurrence of bronzite as a constituent of granite in the Julian Alps.

The type-mass of charnockite.

The mass of rock from which Job Charnock's tombstone was quarried is probably that which forms part of the hill south-west of the powder magazine at St. Thomas' Mount.[1] The north-east and south-west ends of the hill are composed of norite (Nos. 9·657 and 9·660),

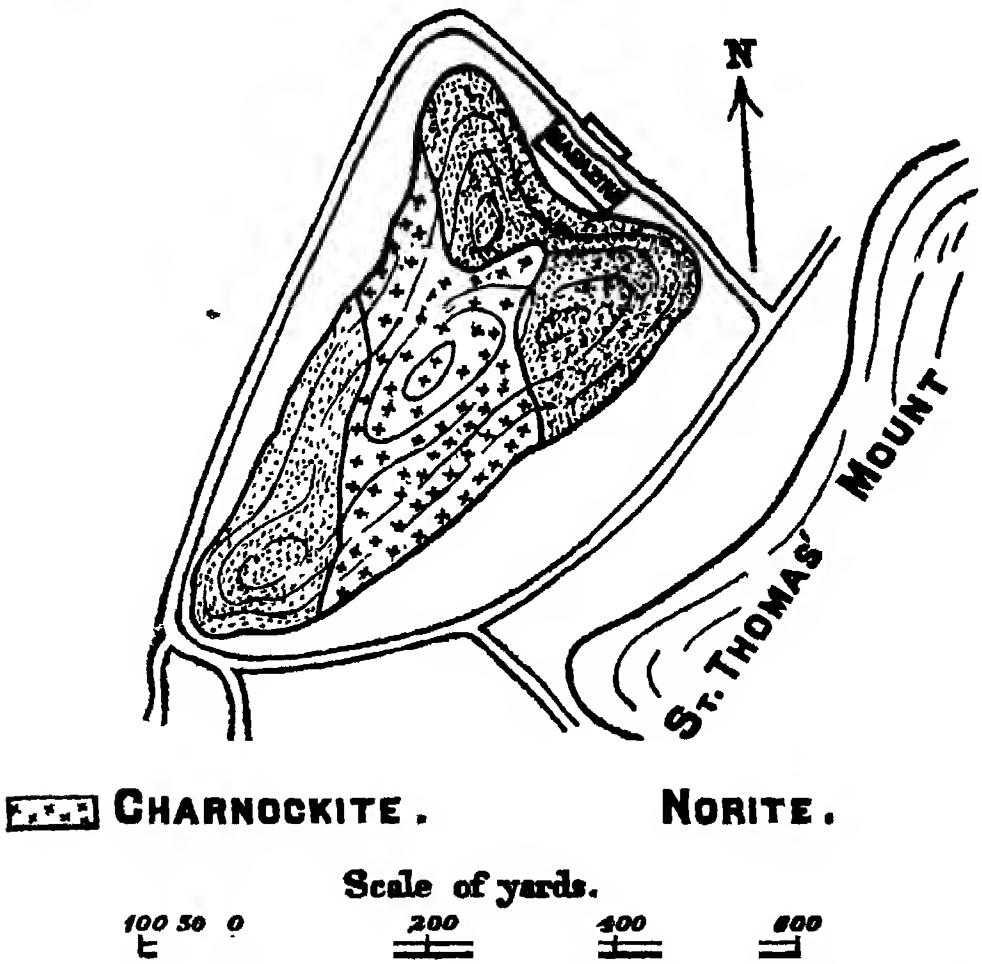

Fig. 1.—*Plan of hill showing the type-masses of charnockite and norite near St. Thomas' Mount, Madras.*

[1] I am indebted to His Grace Dr. P. Goethals, S. J., Catholic Archbishop of Calcutta, for calling my attention to the following passage in the East Indian Chronologist for the year 1801. "Charnock's ponderous tombstone appears to have been cut from the quarries of St. Thomé, as well as most of the tablets in the pristine cemetery of Calcutta" (page 85). This confirms the conclusion based on the petrological resemblance of Charnock's tombstone to the rocks of Pallavaram and the adjoining mass known as St. Thomas' Mount. The rock is still quarried and used for ornamental purposes in Madras; but, as a result of an attempt to get polished samples from a firm in the city, I find the basic norite, with a specific gravity of 3·03, is as often used as the charnockite.

whilst the central mass is composed of charnockite, which is uniform in character up to its junctions on either side with the norite. It is from this mass that the type specimens of the rock, now preserved in the Geological Museum, Calcutta, were obtained (No. 9·658). Through it, and the associated norite as well, run coarse-grained veins—like the contemporaneous veins of ordinary granites—in which the ferro-magnesian silicate and the iron-ores are reduced to mere traces, whilst the rock is made up almost wholly of microcline and quartz (9·659).

Whilst the norite shows practically no signs of a parallel arrangement of its constituents, the charnockite, forming the central mass of the hill, shows by the linear disposition of the dark minerals a rough foliation of north-north-east—south-south-west, being thus parallel to the protaxis which has determined the Coromandel coast-line. If the charnockite, the most acid member, represents the residual portions of the magma whose segregative consolidation resulted in the hypersthene-bearing complex at Pallavaram, it is only natural to expect that one result of its probably late consolidation would be a disposition of its constituents parallel to the fissure it occupied and at right-angles to the direction of maximum lateral pressure. That this rude foliation occurred before and not after consolidation is shown by the fact that the most delicate interlocking structures have been preserved in the rock: the common signs of dynamo-metamorphism, such as peripheral granulation of the constituents and the production of mylonite, are entirely wanting.

Specific gravity.

The determination of a large number of specimens, taken from the type mass near St. Thomas' Mount, gave, as an average of numerous closely agreeing results, a specific gravity of 2·67.

Mineral composition.

Under the microscope, the rock is seen to be an even-grained, crystalline aggregate of quartz and potash felspar as the two most abundant of the constituents, with smaller quantities of oligoclase, rhombic pyroxene, approaching hypersthene in optical characters, opaque iron-ores and an occasional granule of zircon.

Acicular inclusions in the Quartz.

The shapeless crystals of *quartz* are often crowded with minute hair-like inclusions, which are arranged with crystallographic regularity. The crystallographic disposition of two sets of these acicular inclusions are easily studied in sections cut at right angles to the vertical axis (isotropic sections). In such sections (No. 1604, for instance) long acicular inclusions lying in the plane of section (that is, parallel to the basal plane) cross one another at angles of 60° and show straight extinction. The angles formed by the crossing of these long needles are bisected by a set of shorter needles lying oblique to the plane of section. Taking the first set of inclusions to be arranged parallel to the lateral axes, that is, to the lines joining the opposite solid angles of the prism of the 1st order, the second set must lie in the secondary set of symmetral planes, and, being oblique to the basal section, probably lie parallel to some pyramidal face. The numerous black dots seen in the basal sections represent the cut ends of those which in vertical sections are found to lie parallel to the axis of minimum optical elasticity, and, therefore, also parallel to the vertical axis. The three sets of inclusions exhibited by basal sections of blue quartz are shown in the diagram (fig 2).

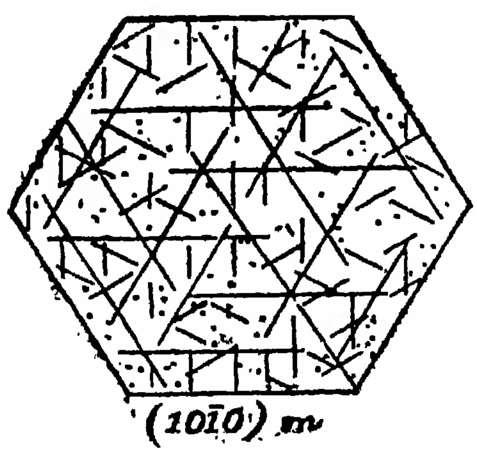

Fig. 2.—*Diagrammatic representation of the needles in basal sections of Quartz.*

On comparing the phenomena presented by the basal sections with those exhibited by longitudinal ones, the assumed positions for two of the sets of needles are easily verified at once. Long

needles lying in the plane of the vertical sections are found on application of the quartz wedge to be parallel to the axis of minimum optical elasticity, which is the vertical crystallographic axis also. These are the needles whose cut ends appear as mere dots in the basal sections. Others are found lying at right angles to the vertical axis, some in the plane of section and some oblique to it; these clearly represent the needles lying parallel to the basal plane and assumed to be also parallel to the lateral crystallographic axes. Besides these there are others lying oblique to the directions of extinction and oblique also to the plane of section. To verify the position of these needles, which are assumed to lie parallel to the rhombohedron, it has been necessary to find a section cut parallel to the prism. Such a section would be one in which the polarisation colours attain a maximum order, and in which long needles should lie in the plane of section, both parallel and perpendicular to the vertical crystallographic axis, whose direction is determined by means of the quartz wedge. Such a case occurs in section No. 1781. In this section it was found that besides numerous needles lying oblique to the plane of the section there were other sets lying in the plane of the section—(1) one set parallel to the vertical axis, (2) another set parallel to the basal plane, and (3) a set meeting the vertical axis at an angle of 52° and meeting the trace of the basal plane at angle of 38°, agreeing thus with the inclinations of the unit rhombohedron in quartz. With the rough means supplied by the cross-wires of a microscope, and in the presence of many other possible planes approximating to the rhombohedron it is dangerous of course to put too much reliance on this determination; but it is worth recording that the determinations made give results which would be expected if it were known that the needles were lying parallel to the face of the unit rhombohedron.

I conclude, therefore, that the hair-like inclusions, to which probably the blue colour of the quartz is due, are arranged with crystallographic regularity as follows:—

(*a*) Parallel to the lateral axes, and thus lying in the principal planes of symmetry.

(*b*) Parallel to the vertical axis.

(*c*) Parallel to the face of the unit rhombohedron and lying in the secondary planes of symmetry.

There may be other sets of needles in some cases, but it is impossible to determine their crystallographic disposition in crystals which are devoid of idiomorphic outlines. The needles lying in isotropic (basal) sections show straight extinction; but, being thinner than the doubly refracting medium in which they are imbedded, further details concerning their optical characters could not be determined.

The hair-like inclusions which occur in the garnets so frequently found to be constituents of the charnockite series I have shown before to be biaxial in their double refraction, exhibiting very wide extinction angles.[1]

Potash-felspar.

The *potash-felspar* is mostly in the form of microcline and often presents the *streifige* appearance due to regularly-arranged intergrowths with a plagioclase to form the microperthitic structure which has been so commonly recognised in the felspars of pyroxenic rocks similar to those of the charnockite series. "Quartz of corrosion" is frequently found in the angular spaces between crystals of felspar. In some of the coarse-grained "contemporaneous veins" traversing charnockite the large crystals of potash-felspar resemble the well-known "moonstone" in presenting an opalescent appearance.

Plagioclase.

The *plagioclase* present appears, from its narrow extinction angles, to approach oligoclase in composition. The fusiform bodies so frequently found in this mineral, and resembling at first sight those which produce the microperthitic structure in orthoclase, possess a higher refractive index and stronger double refraction than their host. Lacroix has referred similar bodies to quartz, regarding their occurrence in the oligoclase as a peculiar form of "quartz of corrosion."[2]

[1] *Rec. Geol. Surv. Ind.*, Vol. XXIX (1896), p. 16

[2] *Rec. Geol. Surv. Ind.*, Vol. XXIV, p. 168

Hypersthene.

The *rhombic pyroxene* seldom presents any noticeable approach to idiomorphic outlines. Whenever definite cleavage cracks are exhibited, the extinction is always straight. I have never found a monoclinic pleochroic pyroxene in the mass of charnockite near St. Thomas' Mount (*vide supra*, p. 126, foot-note). The pleochroism is very distinct, similar to that of hypersthene.

a, reddish brown or bright pink.

b, reddish yellow.

c, green with a bluish tinge.

A greenish-yellow, fibrous, pleochroic mineral resembling *delessite* is often developed along irregular fissures in the hypersthene and is evidently the same as that noticed by Lacroix in the pyroxene of a rock described by him as a "pyroxenic leptynite" from Ceylon. The maximum absorption is parallel to the fibres which is also the axis of minimum optical elasticity.

Accessory minerals.

The opaque iron-ores appear to be referable chiefly to magnetite; titaniferous varieties, however, occur very commonly in the basic associates of charnockite. I have never found a garnet in the unaltered type mass at St. Thomas' Mount, but, as shown below, this mineral is an invariable constituent of the varieties which have suffered from marked dynamo-metamorphism.

Chemical composition.

Chemical analysis shows that the type-mass of charnockite agrees with normal granite in the predominance of potash amongst the alkalies and in the general proportions of the other constituents. The following results (I and II), obtained from specimens collected near St. Thomas' Mount, Madras, are compared with the hypersthene granite of the Ekersund area,

S. W. Norway (III) and an acid variety of "pyroxene granulite" from near Penig (IV).

	I	II	III	IV
SiO_2	75·54	75·30	73·47	72·97
TiO_2	undetermined	trace	0·12	—
Al_2O_3	13·75	11·40	15·42	12·69
Fe_2O_3 } FeO }	4·99	5·40	0·26 0·67	4·55
MgO	0·69	0·60	0·20	0·63
CaO	0·94	0·75	1·35	2·33
K_2O	3·34	6·13	3·64	3·46
Na_2O	1·55	1·45	5 57	3·16
H_2O	0·28	...	...	0·13
	101·08	101·03	100·70	99·92

I. By Dr. T. L. Walker, Geological Survey of India.

II. By Dr. P. C. Roy, Presidency College, Calcutta.

Both specimens of charnockite from St. Thomas' Mount.

III. Hypersthene granite, Birkrem, Ekersund, S. W. Norway. C. F. Kolderup, Bergens Museums Aarbog., 1896, No. V (Abstract, *Neues Jahrb.*, 1899, I, p. 445).

IV. Orthoclase-bearing "pyroxene-granulite", near Penig. Anal. quoted by Zirkel, Lehrbuch, III, 252, and Rosenbusch, Gesteinslehre, p. 486.

Garnetiferous leptynite.

Near its margins, especially where it comes into contact with masses of norite as seen near the railway station at Pallavaram, the charnockite loses its compact texture and dark colour, and passes into a friable, cream-coloured rock, which is sprinkled with pink garnets. The signs of dynamo-metamorphism, so evident in the field, are confirmed by an examination of this rock under the microscope. The weaker minerals have been crushed and are surrounded with granulated selvages, whilst the fragments of quartz show very strongly marked undulose extinctions. The proportion of

quartz to microcline and opaque iron-ores is the same in this rock as in the unaltered charnockite, but instead of hypersthene we have about an equal quantity of irregularly-shaped pink garnets (see Nos. 9·665 and 9·668). The rocks now referred to present the characters of those known to German petrographers as "normal granulite," but the minerals rutile, kyanite, sillimanite, etc., so frequently found in the Saxon granulites do not occur in these rocks at Pallavaram. I have previously detailed the evidence which shows that garnets are developed in rocks of this group at the expense of the pyroxene.[1]

A comparison of this leptynite with the fresh and unaltered charnockite affords interesting examples of the difference between the results of the pressure which brings about a parallel disposition of the rock-constituents before complete consolidation, and that by which the stable minerals, after the solidification of the rock, are smashed into a mylonised mosaic, whilst the pyroxenes are converted into the commonest of all the products of metamorphism, garnets.

The different circumstances under which garnets appear in the charnockite series enable us to indicate the conditions which are favourable to their manufacture. In acid exposures near Pallavaram we have seen that the garnets appear in a rock which only differs from the charnockite in being crushed; but in the basic members of this series garnets are abundant in rocks which do not show the slightest signs of crushing. Clearly then simple dynamo-metamorphism is not essential for their production. This at once suggests an enquiry into the influences of special temperature conditions. We know that by the fusion of garnet we obtain pyroxene amongst the products of the devitrification of the melt. It is also known, from the experiments of Fouqué and Michel-Lévy, that whilst pyroxene is stable at high temperatures, hornblende is the stable form of the same compound at low temperatures. If then our pyroxenic rocks were subjected to dynamo-metamorphism at low temperatures, the pyroxene would be amphibolized and hornblendic rocks would result. Probably, therefore,

Conditions essential for the production of garnets.

[1] "On the origin and growth of garnets and of their micropegmatitic intergrowths in pyroxenic rocks." *Rec. Geol. Surv. Ind.*, Vol. XXIX (1896), p. 20.

some intermediate temperature favours the production of garnet, some temperature short of actual fusion but sufficiently high to prevent amphibolization. If this be so, then we may have garnets produced without dynamo-metamorphism, as in some cases they certainly are. At the same time they may also be produced if the rocks are crushed at high temperatures, which may be high because of the heat produced by the crushing or on account of the depth to which the rock is accidentally buried at the time. In the instance exposed near Pallavaram and illustrated in figs. 4 and 5, the charnockite has been altered probably by the intrusion of the norite, which alone would be sufficient to account for the high temperature accompanying the crushing of the neighbouring charnockite.

Quartz-felspar rocks associated with charnockite.

Although, on account of the absence of hypersthene, these rocks would not, if found isolated, be recognised as members of the charnockite series, yet on account of the facts that they occur as veins in normal charnockite and are composed of the same blue quartz crowded with minute hair-like inclusions, together with a beautifully microperthitic microcline (fig 3), they must be considered to be as

Contemporaneous veins.

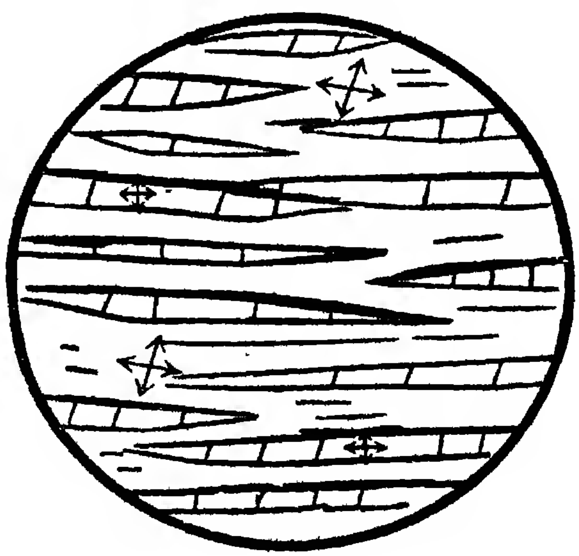

Fig. 3.—*Microperthitic inclusions in the felspar of No. 9· 677. Positions of extinction indicated by crosses.*

much genetic relatives of the charnockites as the common acid "contemporaneous veins" which in granites have always been regarded as the results of the final consolidation of the magma which gave rise to the main masses of the rock they run through. No. 9·659 is an example of such a rock occurring as veins in the typical charnockite near St. Thomas' Mount. These veins run in various directions, but more generally coincide with the linear arrangement of the constituents of the charnockite. Their constituents are arranged parallel to the sides of the veins; but they show no sign of crushing, and this linear arrangement of the constituents must, as in the case of the charnockite of the same mass, be referred to the results of pressure during consolidation.

Whilst on the weathered surfaces it is perfectly easy to distinguish these coarse-grained veins from the fine-grained charnockite through which they cut, it is almost impossible on a freshly fractured surface to indicate the junction between the two, the crystals interlocking to form one rock. The blue-grey colour of the fresh charnockite is precisely that of the quartz-felspar veins which run through it. Sections across the junction examined under the microscope show no abrupt line between the veins and the main mass of charnockite. They differ from the normal charnockite merely in the complete suppression of the hypersthene and concomitant increase in the size of the two remaining constituents, quartz and felspar, which present precisely the same microscopic peculiarities as the constituents of the normal charnockite.

The veins cannot thus be regarded as subsequent and distinct intrusions with a separate origin; they are evidently related to the charnockite, and present all the features which characterise the so-called "contemporaneous" veins of ordinary granites; they would be classed by Reyer as *hysterogenetic schlieren* forming the last phase in the consolidation of the magma from which the associated hypersthene-bearing rocks had previously separated. Larger masses of rock having a similar mineral composition are exposed within the immediate neighbourhood, and in the absence of evidence to the contrary should be regarded also as members of this series.

Similar large masses.

The mass of rock out of which the remarkable Seven Pagodas have been hewn *in situ* is also almost wholly made up of quartz (which is crowded with the peculiar acicular inclusions already described) and microperthitic felspar; but the evidence for connecting this rock with the charnockite series is confined purely to the similarity in the microscopic characters of the two principal minerals (No. 9·677). The rock is coarse in grain, and shows slight signs of kaolinization which gives it a dirty-white colour instead of the blue-green of the normal charnockite. This decomposition which extends to great depths in the rock of the Seven Pagodas, and which enables one at once to distinguish hand specimens of it from the charnockites of the hill masses further inland, is probably due only to the fact that, being near the coast, it has been submerged below the sea during the limited oscillations of level which are shown to have taken place by the deposition of cretaceous and younger marine beds on the Coromandel coast.

The rock of the Seven Pagodas shows on weathered surfaces a very imperfect gneissose structure parallel to the direction of the exposed ridges, and, as Mr. Foote[1] has remarked, parallel to the coast line; that is, N. 5° E. and S. 5° W. But that this foliation was induced before the complete consolidation of the rock seems almost certain, for the crystals are seen under the microscope to be interlocked in a complicated way, and the only definite signs of pressure subsequent to consolidation are indicated by the undulose extinctions of the quartz crystals with an occasional granulation of the more delicate intergrowths.

(2) Intermediate Division.

At St. Thomas' Mount and Pallavaram, the norite and the charnockite form large masses, which whilst being uniform in composition throughout, are very distinctly marked off from one another. Specimens taken from any part of the mass of charnockite will be found to have a specific gravity which never differs greatly from 2·67

[1] *Mem. Geol. Surv. Ind.*, Vol. X (1871), p. 127.

whilst those taken from the mass of norite will be found to be equally constant in their characters and seldom much above or below 3·09 in their specific gravity. These two rocks, therefore, form definite and distinct individuals, the one an acid rock with 75 per cent. of silica, and the other a basic rock with only 53 per cent. of silica.

Apparently composite character of the intermediate group.

But whilst these rock individuals are so well-defined in our type locality, the members of the charnockite series found in other parts of the Presidency generally present no such constancy of characters. Even in a hand-specimen the composite nature of these "intermediate" rocks is generally very noticeable, the basic and the acid portions being either distributed in irregular patches or arranged in parallel bands. This fact makes it very difficult to place any one specimen in the commonly employed system of rock classification.

Whilst the microscope shows an equally marked irregularity in the relative distribution of white and dark elements through the sections of these intermediate members of the charnockite series, one interesting fact presents itself at once, namely, the large number of mineral species represented in each specimen. In fact in nearly all sections of these intermediate rocks *all* the minerals characteristic of charnockite are found mixed irregularly with *all* the minerals of the norites. The commonest variety would thus be described as composed of quartz, orthoclase, plagioclase, augite, hypersthene, hornblende, iron ores, apatite and zircon (No. 9·807; section 1534). Such a mineral list would apply to by far the larger number of specimens of the charnockite series picked up in the Madras Presidency.[1]

In view of the composite nature of these intermediate varieties, one would naturally expect that every gradation between pure norite and pure charnockite ought to occur. This may be true if we take only small specimens into consideration. But by determining

[1] The garnetiferous varieties are not taken into this consideration, as they nearly always show signs of having suffered from dynamometamorphism, and I regard the garnet as a secondary constituent.

the specific gravity of a large number of large specimens, we find that these intermediate members of the charnockite series are comparatively limited in the extent of their variation, and present an average specific gravity of 2·775, seldom being under 2·72 or over 2·84. It is just possible that if we employed larger specimens the range of variation would be still more restricted.

Specific gravity of the Intermediate group.

As an example in illustration of this statement we may take the specimens collected by Dr. H. Warth in South Arcot during his survey of that district in 1893-94. Neglecting the garnetiferous varieties, which are generally greatly crushed and probably have a specific gravity slightly differing from that of the original unaltered rock,[1] we have the following list of specimens from the South Arcot district.

Registered No.	Locality.	Sp. Gr.
9,805	Top of Perumakal hill	2·72
9,813	Tindivanum	2·73
9,786	Kunam village	2·74
9,792	South of Perumbakam hill	2·75
9,785	South-west of Karasanur	2·77
9,791	North-east of Perumbakam hill	2·77
9,800	South-west of Molasur	2·78
9,780	Tirvukarai	2·78
9,783	South-east of Nemeli	2·79
9,779	Tirvukarai	2·80
9,787	Near Kunam village	2·82
9,807	East-south-east of Eraiyanur	2·84
	Average specific gravity	2·774

[1] F. Becke has recently drawn attention to the fact that the minerals formed as the result of dynamometamorphism have generally lower molecular volumes than those of the original constituents from which they have been formed by such secondary processes. The dynamometamorphosed rocks thus contain the elements in minerals which occupy the smallest possible space. ("Ueber Beziehungen zwischen Dynamometamorphose und Molecularvolumen", *Neues Jahrb. f. Min.*, 1896, II, p. 182).

A very closely agreeing result was obtained by me in the Shevaroy hills: 48 specimens taken from different parts of the mass gave an average specific gravity of 2·777.

From analyses made by my colleague, Dr. T. L. Walker, of Nos. 11·915, 9·785 and 9·791, it seems evident that these intermediate forms are composed of about half norite and half charnockite.[1] A fragment having a specific gravity of 2·787 was found to contain 61·40 per cent. silica; one having a specific gravity of 2·818 contained 58·30 per cent. of silica, whilst a third specimen, having a specific gravity of 2·772, contained 63·77 per cent. of silica. A mixture of equal parts of norite and charnockite would have a silica percentage of 64.

It does not necessarily follow, however, that these intermediate varieties of the charnockite series are actually the result of the mixing together of previously differentiated charnockite and norite magmas. On the contrary, the limited amount of variation which they present would be regarded by some as an argument in favour of regarding the intermediate forms as the result of the consolidation of a magma from which, under special conditions developed locally, charnockite on the one hand and norite on the other have been differentiated. That is to say, the large, well-defined masses of charnockite and norite at St. Thomas' Mount would be regarded by some as the more complete separation of the acid and basic rocks, whose intermixture on a smaller scale gives rise to the apparently composite nature of the members of the charnockite series included in this intermediate group.

If the intermediate varieties are really the result of the admixture of charnockite and norite; if, that is, they are only contact products, we ought to expect every gradation between the acid and the basic extremes, which, as has already been pointed out, is not the case. Until, therefore, further observations show that the apparent constancy in the composition of these intermediate varieties is only the result of the limited number of determinations which I have been

[1] On account of the specific gravity of the felspars and quartz being in close agreement the density of the rock fragment does not form a safe index of silica percentage.

able to make, I prefer to claim this point as evidence in favour of regarding the intermediate varieties as the result of the direct consolidation of the original magma, whilst the acid and basic masses are the result of more perfect differentiation favoured by purely local conditions.

Two other facts appear also to favour this view of the case:—

(1) The remarkable resemblance of the charnockite to the norite masses points to the consanguinity of these two extremes. Although one rock is distinctly acid and the other is very basic — one, in fact approaches Bunsen's normal trachytic magma and the other his normal pyroxenic magma in chemical composition — the differences between the two are so well obscured by their remarkable agreement in outward appearances that they are often confused with one another in the field.

(2) The intermediate varieties are the most abundant representatives of the charnockite series in South India, whilst large masses of pure charnockite and pure norite are comparatively rare and restricted in their distribution, thus indicating that their separation has been favoured by local and unusual circumustances.

Although, therefore, the acid and basic extremes so closely resemble Bunsen's *t* and *p* magmas in composition, and although the intermediate varieties at first sight appear to be composite in their characters, I think the facts favour the view that the apparent composite character of the intermediate forms is due only to imperfect differentiation, whilst the occurrences of locally large and distinct masses of charnockite and norite are due to more complete differentiation of the original magma. The phenomena presented by these rocks may be regarded therefore as analogous to those of the augite-diorites (diabases) in which the magma may give rise to a microscopic admixture of augite-diorite and micropegmatite, or may become under other conditions separated into distinct masses of basic gabbro and acid granophyric rocks.[1]

[1] *Cf. Rec. Geol. Surv. Ind.*, Vol. XXX, (1897), pp. 39 and 40; *Quart. Journ. Geol. Soc.*, Vol. LIII (1897), p. 416.

Chemical composition.

A specimen from the typical exposures of the intermediate series in the Shevaroy Hills has been analysed by Dr. T. L. Walker. The specimen had a specific gravity of 2·772, being thus near the average for the group, and the *whole* of the piece used for specific gravity determination was crushed up for analysis and gave the following results :—

No. 11·915 from Arthur's Seat, Yercaud, Shevaroy Hills.

SiO_2	63·77
Al_2O_3	16·30
Fe_2O_3	7·49
CaO	6·33
MgO	2·49
Na_2O	3·68
K_2O	1·21
Ignition	*Nil*
	101·27
Sp. Gr. =	2·772

Microscopical characters.

The minerals which enter into the composition of the intermediate varieties are similar in character to the same species represented in the pure charnockite and pure norite. The quartz is generally the blue or grey variety which is characterised by its hair-like inclusions (*supra*, p. 138). The augite is the pale, blue-green variety (*infra*, p. 156), the hypersthene, highly pleochroic (*supra*, p. 141), and the hornblende is the strongly pleochroic, brown-green, basaltic form described below (p. 158). Opaque iron-ores, zircon, apatite and biotite occur as accessories, as in all varieties of this series. The fact that the same species of minerals present similar microscopic peculiarities in all members of the charnockite series is of course the cause of the striking resemblance which specimens of these rocks bear to one another in macroscopic characters, and which shows their undoubted consanguinity.

Probably the most characteristic features of the intermediate varieties are the *microperthitic felspars* and the *quartz of corrosion*. The quartz of corrosion generally occurs in small patches in which

the quartz presents a pseudo-dendritic arrangement with the felspar; but isolated spindle-shaped blebs also occur in the plagioclase and from their refractive index and double refraction appear to be quartz. These small blebs are in crystallographic continuity with one another over large areas. The fusiform inclusions which give the microperthitic structure to some of the non-striated felspars are generally crossed by cleavage cracks, by which means they are readily distinguished from the small blebs referred to above as doubtfully composed of quartz.

The irregular distribution of the *ferro-magnesian silicates* amongst the other constituents has already been referred to as a noticeable characteristic of the intermediate group (Nos. 9·779 and 9·787). Sometimes only hypersthene is present, in which case this irregularity of distribution is not so marked; but generally both augite and hornblende accompany the hypersthene, whilst biotite, in most cases probably of secondary origin, occurs in nearly all varieties of this group. This tendency of the ferromagnesian silicates to congregate in groups—microscopic patches—was noticed by Hatch in the case of very similar pyroxene granulites from Madagascar (*Quart. Journ. Geol. Soc.*, Vol. XLV (1889), p. 344).

One of the specimens of this group is interesting on account of the large quantities of *graphite* it contains (No. 10·670). Besides graphite, the rock is composed of hypersthene, quartz, an unstriped felspar with microperthitic inclusions, oligoclase, pyrite, titaniferous iron-ore, and a small quantity of garnet.

The large crystals of hypersthene in this rock are extremely well schillerized and the quartz contains the hair-like inclusions noticed before (p. 138). The graphite is scattered in small flakes through the rock and is regularly distributed like a normal constituent. A considerable quantity was easily isolated by means of a heavy liquid from the other constituents of the crushed rock. It floated in the liquid after the precipitation of all the other minerals, and began to sink itself on reducing the specific gravity of the liquid to 2·1. Graphite has recently been found as minute scales scattered

through an elæolite-syenite in the Coimbatore District, its presence therefore in these rocks may be quite consistent with the evidences which indicate their igneous origin. It will be interesting to see if the veins of graphite which occur in Ceylon and Travancore pass through members of the charnockite series.

[Since the above was written an interesting memoir ("Beitrag zur Kenntniss der Gesteine und Graphitvorkomnisse Ceylons") has been published by Max Diersche, giving an account of granulites and pyroxene-granulites collected in Ceylon. The author failed to find graphite as microscopic constituents of these rocks, although the graphite veins occur near the granulites and include fragments of both the ordinary and the pyroxene-granulite (*Jahrb. der k.-k. geol. Reichs.* XLVIII (1898), 241, 257, 279, 284 and 286).]

(3) BASIC DIVISION.

Associated with the charnockite masses at St. Thomas' Mount and Pallavaram, and forming distinct masses uniform in composition over large areas, are rocks which in mineral composition agree very closely with the rocks known generally as *norites*. Norite is one of the many names which, on account of the changes introduced into petrographical nomenclature as a result of the use of the microscope, has undergone a variation in meaning since its first use in 1838 by Esmark. In describing these rocks the word norite is used for rocks composed essentially of plagioclase and rhombic pyroxene, the meaning which has generally been given to it in petrographical literature since the limitations proposed by Rosenbusch in 1877. Under the names augite-norite and olivine-norite I have previously described many of the dyke rocks which cut through the charnockite series in South India.[1] Although there is not the slightest difficulty in distinguishing between these and the members of the charnockite series which have a corresponding mineralogical composition it seems inadvisable to complicate the already confusing petrographical nomenclature by proposing modifications in name to indicate the other differences which are evident in hand specimen as well as under the microscope. The

Use of the term norite.

[1] *Rec. Geol. Surv. Ind.*, Vol. XXX (1897), p. 16.

weakness of our system of rock classification, however, is strongly emphasised by a study of these rocks. In the charnockite series we have large masses of rock composed essentially of rhombic pyroxene, augite and plagioclase, a composition precisely similar to that of some of our black dyke-rocks, and yet no one who has studied these rocks could fail to notice that the norites now under description differ far more from the norite dykes than they do from the acid rock charnockite. To group together a basic rock and an acid one as we do here is contrary to the usual practice of petrographical classification, and yet there can be no more doubt about the close genetic relationship of these two types in South India than there is about the consanguinity of those described by Vogt in the Ekersund area.

Granulitic structure.

The norites are almost always granulitic (panidiomorphic) in structure, neither the ferromagnesian silicates nor the plagioclase showing any noticeable approach to idiomorphic outlines; but when quartz occurs, as it sometimes does in small quantities, it is generally irregularly developed around the other minerals as if it were the last of the constituents to crystallize. Consequently the granulitic structure is more perfectly developed in the varieties free of quartz. The fact that many rocks, which, like marble, have taken on a granulitic structure as the result of metamorphism naturally favours the idea that the pyroxene granulites are metamorphic rocks. But we now know, however, that a granulitic structure may result from disturbance of the magma during the process of consolidation, so the phenomena displayed by these norites belong as much to igneous rocks as to those formed by metamorphism (see p. 239). The dykes of pyroxenite which are associated with, and cut, these norites at Pallavaram are as perfectly granulitic in structure as the norites are and there is no reason to doubt their igneous origin.

Specific gravity.

The norites of the Pallavaram area are very uniform in their specific gravity and by it are sharply marked off from the associated charnockite. The fol-

lowing table gives the average specific gravity of the leading types of hornblende and augite norites :—

No.	Variety.	Sp. Gr.
8·752	Hornblende-augite norite	3·10
8·754	Augite-norite	3·09
9·661	Hornblende-augite norite	3·08
9·395	" "	3·085
9·397	Augite-norite	3·185
9·657	"	3·03
9·656	"	3·11
9·660	"	3·02
	Average specific gravity =	3·09

Augite is almost always associated with hypersthene in these norites, and a peculiar greenish-brown variety of hornblende is found to be extremely common. The augite and the hornblende are remarkably uniform in character in all occurrences of the charnockite series, and are almost as characteristic as the hypersthene. The amount of opaque iron-ore in the norites always exceeds that in the pyroxenites associated with them. A large quantity of the opaque iron-ore is titaniferous. Sphene is typically absent ; it occurs, however, in a biotite-norite near Pallavaram (No. 9·671), but this rock presents many other exceptional characters, and is a distinct departure, for some reason not apparent, from the normal type.

Mineral composition.

The silica percentage, the specific gravity and the great predominance of labradorite amongst the felspars marks these rocks as distinctly basic, as basic in fact as the augite-norite dykes which cut through them.

A partial analysis of No. 9·660 by my colleague Dr. T. L. Walker gave the following results :—

SiO_2	53·38
Al_2O_3	19·38
Fe_2O_3 and FeO	15·39
CaO	7·68
MgO	2·79

Augite-Norite.

The nearest approach to normal norite is the rock which forms the only associate of the type-mass of charnockite near St. Thomas' Mount. Charnockite forms the central mass of the hill whilst augite-norite forms the north-eastern (No. 9·660) and south-western (No. 9·657) ends.

This norite is uniform in structure throughout the mass exposed and specimens have a specific gravity seldom varying by ·05 from 3·025. The foliation is scarcely noticeable except on weathered surfaces.

The principal constituents are hypersthene, augite, plagioclase and opaque iron-ores with accessory apatite, quartz and a felspar that shows no lamellar twinning.

The *hypersthene* crystals are devoid of idiomorphic outline although they generally show a well marked prismatic cleavage and the normal pleochroism, with straight extinction.

The bluish-green colour of the rays vibrating parallel to the axis of minimum optical elasticity $\mathfrak{c}$ in the *augite* is so precisely similar to that of the rays vibrating parallel to the corresponding axis in the hypersthene, that without moving the polariser the two minerals might very easily be confused. The feeble pleochroism and the wide angle of extinction of the augite, however, form a ready means of distinction in polarized light. The colours of the rays vibrating parallel to $\mathfrak{b}$ and $\mathfrak{c}$ only differ from those parallel to $\mathfrak{a}$ by a yellowish tinge in the former and a bluish tinge in the latter. The angle of extinction on the clinopinacoid is about 44°. The crystals very frequently show the characteristic lamellar twinning of augite,

a feature which is never shown by the pleochroic pyroxene that I consider to be rhombic (*vide supra*, p. 126).

The crystals of *plagioclase* are always remarkably clear and fresh. They are twinned both after the albite and the pericline plan. Measurements of the angles between the positions of extinction of adjacent lamellæ in sections across the albite twins seldom vary much from 29°; so the felspar approaches labradorite (Ab, An) in composition.

The crystals of felspar which show no lamellar twinning appear sometimes as Carlsbad pairs, and thus probably indicate the presence of potash felspar; but I have never found a trace of microcline in the norites whose specific gravity exceeds 3. From the abundance of microcline in charnockite one would expect the same structure to appear also in the accessory potash-felspar of the norites, but extended search has so far been unsuccessful, and in view of the fact that plagioclase occasionally shows no twin lamellæ, the evidence in favour of orthoclase must be looked upon with suspicion.

The opaque *iron-ores* are always abundant in the norites, much more so than in the associated pyroxenites. Sometimes they are pyritous; but magnetite, often titaniferous, is the prevailing variety. I have found no green spinel in the norites near Pallavaram, although it is abundant in the non-felspathic associates.

Quartz often occurs intergrown with the other constituents. The quartz-bearing veins show no sharp junction lines with the norites amongst which they ramify, the crystals interlocking across the junction after the manner of segregation and contemporaneous veins.

Apatite, in short prisms, is always more abundant in the norites than in the associated charnockite.

An occasional granule of *zircon* is found in almost every slide. So far as my experience goes, *sphene* never occurs in the unaltered varieties of norite.

Hornblende-Augite Norite.

The most prevalent variety of the basic forms of the charnockite series is one in which hornblende, as well as augite and hyper-

sthene, are the ferromagnesian constituents. Rocks of this kind are represented especially well in the hill-mass east of the railway station at Pallavaram (Nos. 8·752, 9·661, 9·667) and also in the Pammal hill, west of the railway (No. 9·395).

The hypersthene, augite, felspar and accessory minerals are apparently of the same kind as those already described as constituents of the augite-norite obtained in the neighbourhood of St. Thomas' Mount.

The hornblende is the peculiar deep green-brown, highly pleochroic variety which seems to be characteristic of these rocks and of their ultra-basic associates. Its crystals are often larger than those of the augite and hypersthene, sometimes giving the rock in consequence a feeble porphyritic aspect on weathered surfaces. The crystals are generally elongated parallel to the vertical axis and in cross-sections the characteristic cleavage is extremely well marked. The pleochroism is—

$\mathfrak{a}$=pale yellow to bright yellow.
$\mathfrak{b}$=brown.
$\mathfrak{c}$=brownish green.

The absorptions for $\mathfrak{b}$ and $\mathfrak{c}$ are about equal, both being much greater than for rays vibrating parallel to $\mathfrak{a}$. The extinction angle ($c:\mathfrak{c}$) is very narrow, and, on account of the great absorption, difficult to measure precisely.

Biotite-Augite Norite.

The basic rock described under this name forms an exceptional type amongst the charnockite series and appears to be very limited in its distribution. Biotite is extremely common as an accessory amongst the intermediate and basic members of the series, but it is generally small in quantity compared with the hypersthene, augite and hornblende, and from its intimate association with the hornblende appears to be, in part at least, of secondary origin. In this particular rock, however, it presents its crystal-outlines against both the augite and the

Aberrant form of norite.

hypersthene, and in crystallizing at such an early stage has apparently taken up most of the iron ; for both the rhombic and the monoclinic pyroxene are most unusually pale, almost colourless in fact, in section. Another point which marks off this rock as an abnormal form is the presence of a considerable quantity of sphene, the titanic acid being in normal members of the charnockite series characteristically confined to ilmenite. The quantity of opaque iron-ore in this rock is consequently much smaller than in the normal norites, and most of it is in the form of the sulphides, pyrite and pyrrhotite.

A distinct mass of this rock occurs about one mile east of the railway station near Pallavaram (No. 9·671). Specimens have an average specific gravity of 2·96, and are composed of a pale enstatite with very faint pleochroism, colourless augite, plagioclase, a little quartz, magnetite, pyrite, pyrrhotite, apatite in numerous short prisms, brown pleochroic sphene and a deep-brown biotite with strong pleochroism and very narrow optic axial angle. The pyroxenes show a marked tendency to ophitic development around the other minerals which is another feature quite exceptional in the charnockite series. Although the association of this rock with the normal members of the charnockite series, and the presence in it of considerable quantities of rhombic pyroxene, necessitate its inclusion in the series, I am unable at present to recognise any peculiar conditions in its occurrence which would account for the distinct departure from the normal characters which it shows under the microscope.

A rock on the western margin of Pammal hill, west of Pallavaram (No. 9·675), shows by the large quantity of biotite in it an approach to this strange variety ; but it agrees nevertheless more nearly with the normal type in the absence of sphene, and in the more marked pleochroism of its rhombic pyroxene. This rock also contains a large proportion of quartz and is situated, apparently forming a passage, between normal augite-norite, which forms the central mass of the hill, and a garnetiferous, more acid, form, also with biotite, forming the north-western margin of the same mass.

Types rich in Garnet.

In the immediate neighbourhood of Salem there are several occurrences of the garnetiferous basic members of this series forming small, bare, rocky hills with apparently a lenticular outline; the hill immediately W.-S.-W. of Salem and Nagaramalai near the Chalk Hills to the north of the town are good examples—Nos. 9·683, 9·684, 11·895, 11·903. These are presumably amongst the rocks referred to by Lacroix[1] as members of his "pyroxenic and hornblendic gneiss, (*l*)", and which, quoting Leschenault's labels, he says forms the valley of Salem. It is a little difficult to say what is meant by the valley of Salem; but these rocks are certainly not the most abundant in the neighbourhood of the town, although, on account of the abrupt little hills they form, and on account of the conspicuous garnets they contain, it is likely that they would figure largely in the "bag" of an amateur collector.[2] This particular type very commonly occurs in such lenticular masses in the schists and old biotite-gneisses of the plains in the immediate vicinity of large mountain masses like the Nilgiris and the Shevaroys. Those referred to here, for instance, as occurring in the vicinity of Salem entirely resemble the little hillocks which fringe the foot of the Nilgiris in the Bhavani valley.

These rocks are generally but not always coarser in grain than the average basic varieties of the series. Sometimes they are very hornblendic and at other times are comparatively free of hornblende. In general the optical characters of this mineral and its fellow ferro-magnesian silicates are in agreement with the data already recorded for the other members of the series described above.

Garnets.

One interesting peculiarity is the frequent correspondence in the intensity of colour shown by the hypersthenes and the garnets. Without turning the

[1] *Rec. Geol. Surv. Ind.*, Vol. XXIV, p. 175.

[2] Leschenault de la Tour's only published reference to the exposures of these rocks south-west of Salem is as follows:—"Une montagne dans le sud-ouest (of Salem) est presque entiérement formée de roches où l'amphibole domine, et sur la surface desquelles des grenats grossiers et opaques sont disposes par plaques." (*Mem. du Mus. d'hist. nat.*, Vol. VI (1820), p. 343).

polariser one might very well confuse the pink of the hypersthene with that of the garnet. The garnets are often very irregular in their shape and spongy in structure on account of the inclusion of numerous vermiform or otherwise-shaped pieces of white mineral (quartz or el spar) which I regard as the acid bye-product separated during the break-up of the pyroxene to produce garnet. Sometimes the garnets form a sort of corona to the hypersthenes, and all stages are found from a narrow ring around the pyroxene to a complete broad ring of garnet surrounding a core of granular quartz (Plate VIII, fig. 6).

Schiller phenomena and acicular inclusions.

In common with all the rocks in the neighbourhood of the Chalk Hills the rocks of Nagaramalai are schillerized. The most interesting form of schillerization is displayed by the garnets, which contain numerous needles possessing a high double refraction with a wide extinction angle up to as much as 39°. These needles are arranged with a remarkable regularity of crystallographic disposition within the garnets, as described in a previous paper.[1] Needles apparently similar in crystallographic disposition and somewhat similar in optical characters were noticed by Harker in the garnets of an eclogite from Port Tana, N. Norway, and were referred to as kyanite on account of the wide extinction angles which they exhibited.[2] In the garnets of a pyroxene-granulite found near the peridotite of Elliott County, Kentucky, Diller found what appears to be similar inclusions, which he says are arranged at angles of 45° to one another, and are distinctly monoclinic with a maximum extinction angle of 30°.[3]

Lacroix, on the other hand, has referred to rutile regularly arranged needles in the garnet of rocks which he has described as basic pyroxenic and hornblendic gneiss from Salem and Ceylon.[4]

[1] *Rec. Geol. Surv. Ind.*, Vol. XXIX (1896), p. 16.

[2] *Geol. Mag.*, 3rd decade, Vol. VIII (1891), pp. 170, 171. In his "Petrology for Students" (p. 300), Harker refers to these needles as rutile, although in his original paper he says they exhibit extinction angles up to about 31°, whilst rod-like, reddish-brown crystals of rutile were found in the same rock, which I find to be the case also with the rocks of Nagaramalai.

[3] *Bull. U. S. Geol. Surv.*, No. 38 (1887), p. 27.

[4] *Rec. Geol. Surv. Ind.*, Vol. XXIV (1891), p. 176; translation from *Bull. de la Soc. Min. de Fr.*, Vol. XII (1889), p. 311.

These needles, he says, exhibit a positive double refraction and give straight extinctions. It is now practically certain, however, that the particular rocks referred to in this connection came from the immediate neighbourhood of Salem town and are very similar in composition to those occurring at Nagaramalai, which, as already stated, contain inclusions with quite different physical properties. I have found very similar acicular inclusions in the garnets of the charnockite series in other parts of the Madras Presidency, particularly on the southern flanks of the Nilgiri Hills, but in all cases the needles show a wide extinction angle.

It is impossible to determine with certainty the mineralogical nature of needles so exceedingly minute. Harker referred those in the Port Tana eclogite to kyanite, a mineral which has frequently been found in eclogites, and the narrow extinction angles which kyanite displays in brachypinacoidal sections would make it a difficult matter to distinguish small needles of the mineral from monoclinic crystals, as they have been considered to be by Diller and by myself. Having obtained extinction angles up to as much as 39,° I favoured the idea that the needles might be sphene. The fact that they are often black and opaque for a portion of their whole length might then be due to replacement by ilmenite.

It is certain, however, that they are not rutile, although the hair-like inclusions in the blue quartz of the charnockite series may be so nevertheless, as they invariably show straight extinctions in horizontal sections of the quartz (*vide supra*, p. 138). Titanic acid introduced into quartz might remain pure and might crystallize as rutile needles; but the same substance introduced into a garnet might be changed to a titanate of some protoxide. It is not without interest that the plates and rods which give the schiller appearance to hypersthene, and which are very abundant in the hypersthenes of the Nagaramalai rock, have also been referred to titanic acid by Kosmann, Törnebohm, Brögger and others, although the different authors are not agreed as to the precise origin of the inclusions. Whatever they are in composition—and there is little doubt about the fact that

they are not precisely the same mineralogically in all the rocks—there must be some agreement in the conditions under which they have originated; for when these needles appear in the garnets the accompanying quartz crystals are always crowded with acicular inclusions and the hypersthenes beautifully schillerized. When, on the other hand, garnets are free of such acicular inclusions, the quartz is also clear and the rhombic pyroxenes belong to the variety which Professor Judd has referred to as proto-hypersthene. It seems to me that the simultaneous appearance of these similar phenomena in all the constituents of the rocks must be regarded as the result of secondary causes, and the theory which is most in agreement with all the facts of the case is that for which Judd has proposed the term "schillerization."[1]

Although from the evidence obtained from hypersthene alone, it may be difficult to show any great objection to the theory that the schiller plates are the result of infiltration along cleavage planes; such a theory could not account for the regularity of crystallographic disposition of the needles in the accompanying garnets and quartz, nor could it account for the fact that the inclusions in the hornblende of these rocks are arranged, not parallel to the cleavage planes, but parallel to an axis of optical elasticity. It seems much more likely that the action of secondary chemical agents displays itself by phenomena developed in directions definitely related to the axes which determine the crystal-form as well as the other physical properties of the mineral. If, also, negative crystals are produced by solvents acting more effectually along planes of chemical weakness, then the composition of the mineral acted on will naturally influence the nature of the product and of the substance forming the schiller plate or rod. From this it follows that when the constituents of a rock are schillerized, the rods, plates or needles will vary in composition according to the chemical nature of the mineral which is acted on.

[1] *Quart. Journ. Geol. Soc.*, Vol. XLI (1885), p. 408; *Min. Mag.*, Vol. VII (1886), p. 81.

(4) ULTRA-BASIC DIVISION.

Pyroxenites.

Besides the instances of *Schlieren* described (p. 215) as due to a partial or complete local failure of the plagioclase, pyroxene-rocks occur also as narrow dykes cutting through the norites at Pallavaram. In the Pammal hill, two miles west of the railway station, these dykes are found to be from 3 to 5 feet wide, and are seen distinctly to bifurcate with branches proceeding in different directions through the norite (Nos. 9·394, 9·672). Near the summit of one of the hills on the eastern side of the railway line at Pallavaram there is an exposure of what appears to be a vein 9 inches wide of the non-felspathic rock in a hornblende-norite (No. 9·667). The absence of all signs of chilled edges, such as are distinctly shown for instance by the trap dykes when they cut through the charnockite series shows that the norites were probably still hot when the pyroxene-rocks were intruded, and in the last-mentioned instance, where it is easy to obtain microscopic sections across the junction, the sharpness which the line presents to the naked eye is not so apparent when the crystals are magnified. Under the microscope the two rocks are seen to differ only by suppression of felspar in that forming the vein; there is no change in either the size or relative proportion of the ferro-magnesian silicates, and the crystals interlock across the junction line. What, therefore, might be looked upon on account of its limited exposure, as an intrusive vein in the field is really more of the nature of an ultra-basic segregation. As this rock only differs from the norite (No. 9·667) in which it occurs, and which has already been described (p. 157), in the absence of felspar, no further details as to its characters need be given.

The non-felspathic types, however, of Pammal hill to the west of the railway station at Pallavaram form undoubted dykes, and on account of their ramifications must be regarded as intrusive in the norites. In these cases, also, the intrusions must have taken

place whilst the norites were still hot, as no signs of chilled edges are noticeable, and this fact, together with the similarity in mineralogical characters between the ferro-magnesian minerals composing the dyke-rocks and those entering into the composition of the associated norites, point to the genetic relationship of the two rocks notwithstanding the undoubted differences between their periods of consolidation.

These pyroxenite dykes often show a slight banding as if successive injection had occurred. A case is illustrated by No. 9·672 in which bands of pure pyroxene-rock alternate with hornblendic bands without, however, a sharp junction line between them (Slide No. 1438).

In describing the basic dykes which cut through the charnockites and other massive rocks in South India I have referred to the occurrence of enstatite-bearing rocks which also approach pyroxenites in composition,[1] but there is no doubt about the differences between those (which are relatives of the supposed Cuddapah traps) and the pyroxenites now under consideration, which are relatives of the older charnockite series. Although the constituent minerals belong to the same species in both cases the crystal-habits are sufficiently marked to enable a distinction to be readily made even in a microscopic section. If this conclusion be correct we ought to find instances of trap dykes of the kind described in the paper just referred to cutting across pyroxenite dykes of the kind occurring in the Pammal hill and now under description. The absence up to the present of evidence of this kind I prefer to attribute to the limited number of observations hitherto made.[2]

[1] *Rec. Geol. Surv. Ind.*, Vol. XXX (1897), p. 30.

[2] Mr. Middlemiss has called my attention to two dykes exposed at a point 6 miles south of Royakotta in the Salem District, which in my opinion ought to be regarded as evidence in support of this conclusion. One of the dykes is a pyroxenite similar in character to those described in this paper as ultra-basic members of the charnockite series. It has a specific gravity of 3·31 and is composed of a medium to fine-grained mixture of hypersthene, often schillerized, and pale augite with brownish-green hornblende, without white minerals and practically devoid also of opaque iron ores. These characters it will be seen agree with those of the pyroxenites of Pammal hill near Pallavaram. This rock is cut through by a later dyke which is undoubtedly similar to the rocks generally regarded as the dyke-representatives of the Cuddapah lavas, and in mineral composition and structure is related to those which I have described under the name augite-norite (*Rec. Geol. Surv. Ind.*, Vol. XXX, p. 27).

The non-felspathic forms of the pyroxenic rocks may be divided into the following leading types:—

(*a*) Types rich in hypersthene.

(*b*) Types rich in hornblende passing into amphibolites.

(a) Types rich in hypersthene.

The purer forms of pyroxenite forming dykes in the norites west of Pallavaram are perfectly granulitic in structure and are composed of hypersthene, brown hornblende and augite, with small quantities of olivine, green and black spinelloids and occasionally apatite. In rocks where the microscopic structure is so perfectly granulitic as in these pyroxenites it is impossible to determine the relative ages of the constituent minerals with certainty. It is an interesting circumstance to find that the granulitic structure of the norites described above is so perfectly displayed also by their ultra-basic relatives whose intrusive characters can hardly be doubted.

A chemical analysis of No. 9,394, by Dr. T. L. Walker, gave the following results:—

SiO_2	46·86
Al_2O_3	9·80
Fe_2O_3 and FeO	16·35
CaO	9·57
MgO	18·08
Alkalies	traces
Ignition	0·67
	101·33

Sp. Gr. = 3·333

Hypersthene is by far the most abundant constituent of the Pallavaram pyroxenites (Nos. 8·756, 9·394, 9·672). It is a highly pleochroic variety, probably approaching in composition the varieties of rhombic enstatite for which Judd has proposed to revive Vom Rath's term *amblystegite*. The crystals are very frequently schillerized, with the development of brown-red plates similar to those of the well-known hypersthene of St. Paul.

The *augite* is almost colourless and is far less abundant than the *brown hornblende*, which is somewhat similar in its optical characters to the hornblende occurring so commonly in the associated norites. Crystals of the latter mineral give a maximum extinction angle on (010) of 16° and are strongly pleochroic—

$\mathfrak{a}$ = pale yellow.
$\mathfrak{b}$ = deep brown.
$\mathfrak{c}$ = deep greenish brown.
$\mathfrak{b} = \mathfrak{c} > \mathfrak{a}$.

They are often schillerized by black needles and plates, the needles being generally arranged parallel to a direction of extinction and therefore inclined to the cleavage cracks.

Olivine appears to be irregular in its distribution in these rocks. In some slides (No. 1438) it appears in considerable abundance as small, irregular crystals, which are cracked in characteristic fashion, with formation of a yellowish-green serpentine. The high index of refraction, strong double refraction, absence of colour and the characteristic fracture and secondary alteration leave no doubt as to the identity of this mineral, although its appearance as an accessory mineral in pyroxenite is so exceptional. In a rock, however, in which the large predominance of hypersthene shows that the percentage of alumina is low, whilst the protoxides of iron and magnesia are in large quantity, the appearance of olivine in the least siliceous types would naturally be less surprising than in those in which the predominating pyroxene is of the aluminous, monoclinic varieties. The present instance, therefore, forms an interesting example of a link between the pyroxenites and the peridotites.

Green spinel similar to pleonaste and hercynite in appearance is very commonly found in these rocks, and appears to be a common constituent or associate of such pyroxenic rocks all the world over. As a constituent it appears in the pyroxene rocks and sometimes in the basic norites. As an associate it occurs amongst the products (apparently) of contact metamorphism; under the latter circumstances it is a very constant associate of corundum. The late G. H.

Williams found these two minerals, together with sillimanite, in the Cortlandt series of New York,[1] and compared the occurrence with the previously better-known similar association of these minerals with the pyroxene-granulites near Ronsberg on the eastern edge of the Bohemian forest, whilst very numerous similar instances have recently been found in South India.[2] The occurrence of the green spinel as a simple constituent of the series as well as a contact product of the pyroxenic rocks adds another instance to the already numerous examples which show that the distinction between simple igneous rocks and highly metamorphosed products cannot be marked by a sharp line.

The green spinel in these pyroxenites occurs in irregularly shaped granules and sometimes vermiform blebs, associated invariably with lumps of magnetite and generally crowded with minute granules and dust of presumably the same substance. Where the crystallization has been very coarsely developed we frequently find cubic crystals of magnetite lying in the green spinel, which, except in the immediate neighbourhood of the magnetite crystals, is crowded with magnetite dust. From the immediate precincts of each magnetite crystal the dust has been completely removed and a clear green zone indicates the extent of its "crystal court."

In one case of a hypersthene pyroxenite from the Salem District (sections 1030 and 1031) the green spinel is generally seen to be surrounded by a zone of a pale-pink, isotropic and highly refracting mineral, which is presumably the ordinary magnesia-alumina spinel.[3] In this case, therefore, the spinelloids are represented by three different types formed apparently in an order which indicates a gradual decrease in the protoxide and sesquioxide of iron and a

[1] *Amer. Journ. Sci.*, Vol. XXXIII (1887), p. 194.

[2] See Manual of Economic Geology of India, 2nd Edition, 1898, pp. 12, 13, 14, 18, 41 and 45.

[3] The specimen from which these sections were cut I found in the Madras Museum labelled "Salem district," but without any further details as to its origin. Judging from the slides the rock must be a most remarkably interesting one, and it is extremely unfortunate that in consequence of the absence of details as to its precise locality we are unable to examine its geological relationships.

corresponding increase of magnesia and alumina amongst the consolidating oxides. The order of crystallization is thus :—

(1) Magnetite . . . . $FeO.Fe_2O_3$.
(2) Pleonaste (Ceylonite) $(Mg.Fe)O.(Al.Fe)_2O_3$.
(3) Spinel . . . . $MgO.Al_2O_3$.

(b) *Types rich in hornblende.*

In many places it is found that the non-felspathic types of the charnockite series are characterised by the predominance of hornblende over the other ferro-magnesian silicates, so that the rocks would be more accurately described as pyroxene-amphibolites. But as it seems certain from the evidence obtainable in places like Tirrupur in the Coimbatore District, that the amphibole has in part been formed by alteration of the pyroxene, it is better to recognise the genetic relationships which these highly hornblendic types bear to the purer pyroxenites than to separate them under the name amphibolite, which would more correctly express their present mineralogical composition.

In one of the specimens (No. 9·317) obtained near the Travellers' bungalow at Tirrupur, there are very pretty instances illustrating the change from augite to hornblende; patches of the latter mineral are scattered through the large augites, showing, by their simultaneous extinction, a crystallographic parallelism to one another, and by the cleavage cracks, an axial parallelism also to the augite from which they have been derived. Although this specimen contains considerable quantities of felspar, the ferro-magnesian silicates, augite, hypersthene and hornblende, which it contains, are precisely similar in character to the representatives of the same species forming the associated ultra-basic masses. Near the Travellers' bungalow at Tirrupur, narrow dykes or veins of a sparkling black amphibolite (No. 9·309) are found ramifying amongst the granulitic rocks which are composed, as already stated, of augite, hypersthene, hornblende and felspar. These dykes of amphibolite bear to the felspathic rocks

Amphibolization of the Pyroxenes.

which they cut a relation precisely similar to that existing between the pyroxenites and norites of Pallavaram (see plate IX).

The hornblende in these rocks is of two kinds, a blue-green actinolitic variety occurring as patches in the pyroxenes and evidently secondary, and a dark, brownish-green, basaltic variety occurring both in large crystals and as patches in the pyroxenes. This also in part, at least, appears to be of secondary origin. It has a very deep pleochroism and exhibits a very narrow extinction angle ($c : \mathfrak{c}$), which on account of the great absorption, it is impossible to measure with precision. The crystals are often twinned parallel to the orthopinacoid (100), cross-sections showing both the trace of the twinning plane and the prismatic cleavage very distinctly.

So far as my experience goes, whenever hornblende becomes a prominent constituent of these ultra-basic representatives of the charnockite series, the associated felspar-bearing types—the norites, that is—have also a conspicuous amount of hornblende amongst their constituents. Besides the instances at Tirrupur in the Coimbatore District, there are good examples illustrating this fact in the South Arcot District. At the south-west base of Vitlapuram hill, for instance, we have a good example of a rock composed of pale pyroxene and dark-green hornblende (No. 9·809), whilst a hornblende-augite norite forms the summit of the same mass (No. 9·810).[1] This fact also supports the conclusion that the ultra-basic rocks are true relatives of those which contain felspar, and that they only differ from the latter merely in the local suppression of the white minerals. Sometimes they appear as basic *schlieren;* at other times they form distinct and ramifying veins, which must be regarded as intrusive. But the absence of chilled edges, and the similarity of peculiarities amongst the ferro-magnesian silicates, show that the pyroxenites and amphibolites were intruded whilst the norites were still hot, and also that they have been derived from the same magma as that which gave rise to the norites.

[1] A somewhat similar arrangement of ultra-basic forms with regard to the felspathic and quartz-bearing types is seen in the Shevaroys, the rocks composed of pure ferro-magnesian silicates occur near the foot of the ghât leading to Yercaud, whilst the upper parts of the hill are often as acid as pure charnockite.

CHAPTER V.

Description of the Principal Exposures.

It has already been pointed out that notwithstanding the great variations in silica percentage which the members of the charnockite series present, they exhibit distinct characters, both microscopic and macroscopic, which readily serve to group them together, and which point to the unmistakable consanguinity of the different varieties. Partly because their true mineralogical characters were not recognised before the microscope was used in South Indian petrology, and partly because the earlier surveyors were compelled for economic reasons to confine their attention to isolated areas, this very important fact was not recognised before 1892. Some members of the charnockite series have been referred to as "quartzo-felspathic gneiss," others have been spoken of as "hornblendic gneiss," whilst in other localities they have been mapped as "syenitoid gneiss." This system of nomenclature has resulted firstly, in the separation from one another of the different members of one series of related rocks, and secondly, in the grouping together of rocks, which, though composed of the same mineral species, are not genetic relatives of one another. In consequence of these unfortunate circumstances, for which only the great petrological progress of recent years is to blame, only a small portion of the voluminous literature of South Indian geology can be made use of in summarising the facts concerning the geological relations and geographical distribution of the rocks now grouped together under the name "charnockite series."[1]

The Type-Exposures near Madras.

On account of their proximity to the city of Madras, the

[1] Mr. R. B. Foote has, by referring to the rock at Cape Comorin as a type, given a convenient means for identifying the members of the charnockite series in the districts of Madura and Tinnevelly. ("On the Geology of the Madura and Tinnevelly Districts," *Mem. Geol. Surv. Ind.*, Vol. XX, p. 28.) It is unfortunate that this practice of supplementing the mineralogical description of a rock series by reference to a local type has not been universally followed in our publications.

exposures of the charnockite series at St. Thomas' Mount and the adjoining hills of Pallavaram may be conveniently placed first in the list of occurrences of this series in South India. It is from this locality that large quantities of the rocks have been quarried for structural and ornamental use in Madras, and it is from the neighbourhood of St. Thomas' Mount that the rock of Job Charnock's tombstone was obtained (*vide supra*, p. 134).

Charnockite and Norite.

The low hill on the west side of St. Thomas' Mount is composed of a mass of charnockite in the centre, with masses of augite-norite on the north-east and south-west sides. The central mass has been selected as the type mass of charnockite (No. 9·658), whilst the sides may be regarded as type examples of augite-norite (No. 9·657 on the south-west side, and No. 9·660 on the north-east). Both rocks are penetrated by veins (contemporaneous veins) of a rock composed mainly of blue quartz and microperthitic microcline which on account of its coarse grain may be called charnockite-pegmatite (No. 9·659).

Charnockite-pegmatite.

The main mass of St. Thomas' Mount itself is augite-norite which, however, is so cut through by acid veins, that in places the rock becomes an irregular mixture of charnockite and norite such as characterises the varieties described as "intermediate."[1]

St. Thomas' Mount, or "The Mount" as it is often called in Madras, is only eight miles south of the city, on the South Indian Railway; so the locality is easily visited during the time that most of the steamers are delayed in the harbour. The type-exposures are thus easily examined by visitors who may not be able to make a tour through the Presidency. The hill rises to about 250 feet above the sea-level and is crowned by a curious old church built by the Portuguese in 1547.

The railway station of Pallavaram, 3 miles further south on the South Indian Railway, is situated between the Christian village (Isa-Pallavaram) and a

Garnetiferous leptynite.

[1] The common occurrence of what Lossen called *Primärtrümer* in this series is referred to in another section of this paper (p. 218).

number of low rounded hills which lie on the east side of the line, forming an irregular range not exceeding 500 feet in height. The rocks immediately east of the line are garnetiferous leptynite, which are here regarded as the result of the metamorphism of the charnockite. Whilst the normal charnockite is a compact, dark-grey rock which breaks with a semi-conchoidal fracture, the garnetiferous leptynite is dirty-white in colour, is more distinctly foliated and crushes easily under the hammer. The blue quartz, however, which is so characteristic of the charnockite series, retains its colour in this leptynite, but instead of hypersthene the rock is sprinkled with garnets. Microscopic examination shows that this rock, like charnockite, is composed largely of quartz, microcline and opaque iron-ores, whilst pink garnets appear to replace the original pyroxene. The crushed character of the rock bears evidence to the dynamic action to which it has been subjected (No. 9·665).

The leptynite is limited on the north and south sides by two rocky ridges, which mark its junction with the normal charnockite. These ridges are generally rust-coloured through the decomposition of pyrite, which occurs in large quantities near the margins of the leptynite. A depression between the exposures of leptynite shows masses of norite cropping out in a gully.

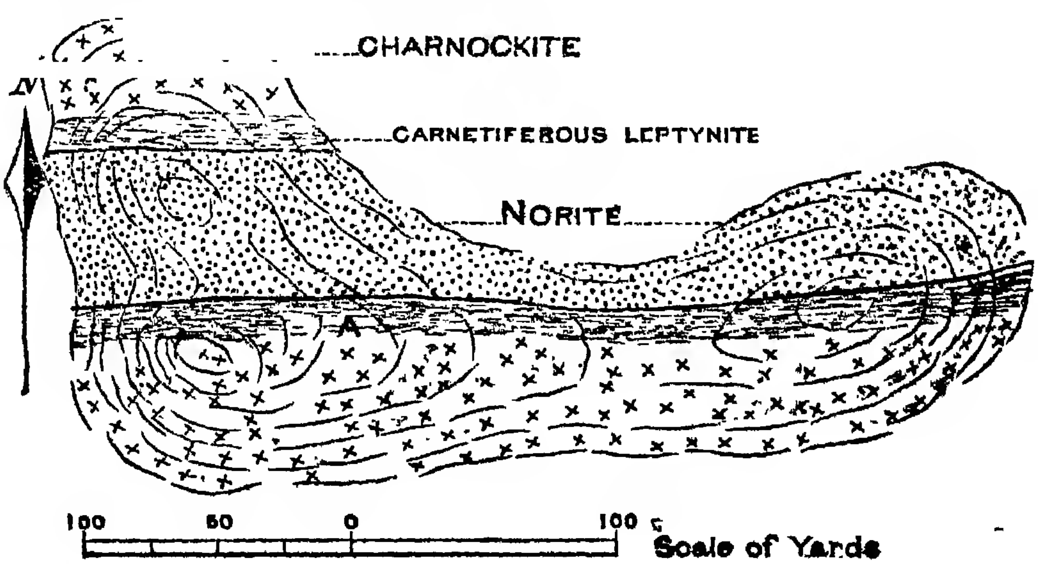

Fig. 4. Plan of hill near Pallavaram, showing the zones of leptynite between the norite and unaltered charnockite.

The hill on which this garnetiferous leptynite occurs is separated from a number of quarries further east by a narrow tract of alluvium running N.-N.-E. and S.-S.-W.[1] At the southern end of the quarries the leptynite is again found associated with charnockite, the junction line being obscured in a rubbish-covered gully. About a mile E.-S.-E. of this point a further occurrence of leptynite associated with charnockite shows a gradual passage from the former (No. 9·668) to the latter (No. 9·669). This occurs on both sides of the central mass of norite, which is thus fringed by leptynite and charnockite. The facts revealed at this point leave little doubt as to the secondary origin of the characters which serve to distinguish the leptynite from normal charnockite.[2]

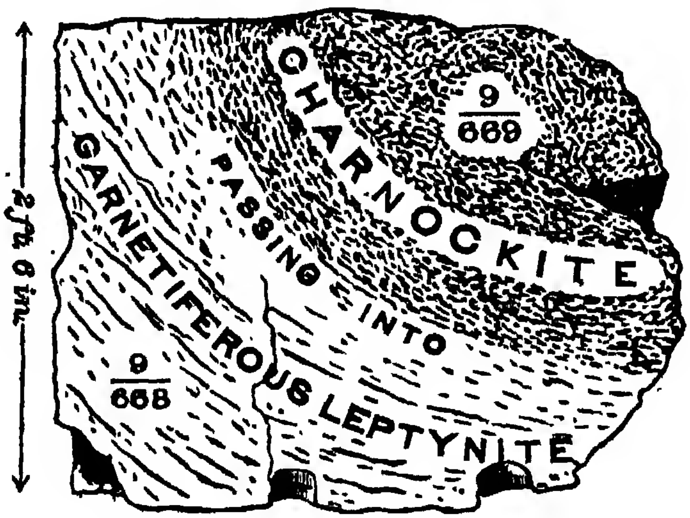

Fig. 5. *Sketch of block occurring at A in fig. 4, and showing the gradual passage of charnockite into leptynite.*

Between this hill and the quarries referred to above occur the exposures of the peculiar biotite-bearing rock described on p. 158, near which is found the graphite-bearing variety of the "intermediate" group of this series (p. 152).

The principal exposures of norite on the east side of the

[1] From these quarries the rock used in the Madras Harbour works has been largely obtained.

[2] See also p. 142. For further evidence as to the formation of garnets from pyroxenes, see *Rec. Geol. Surv. Ind.*, Vol. XXIX, p. 20.

railway occur to the north of the leptynite and charnockite. The most abundant variety is that in which both augite and basaltic hornblende accompany the hypersthene. In some cases the hornblende crystals are distinctly larger than the other constituents, and by their more rapid decomposition on weathered surfaces give the rock a spotted appearance (Nos. 8·752 and 9·661). Sometimes, however, the hornblende is practically absent, whilst augite and hypersthene are associated in about equal proportions with the plagioclase and opaque iron-ores (No. 9·397).

On the west side of the railway station the charnockite series is represented in the Christian village, Isa Pallavaram, by a garnetiferous and micaceous variety, resembling, apparently, the peculiar biotite-bearing rock referred to on p. 159.

The sections exposed in the wells near the village show the prevalence of a coarse-grained quartz-felspar rock resembling that which veins the charnockite at St. Thomas' Mount. Although the rock is generally much decomposed, the quartz crystals retain the characteristic blue colour of this series. Sometimes fragments of garnet and biotite occur in this rock. Further exposures appear rising like islands through the alluvium of the paddy-fields to the west. Rounded lumps of black rock mark the outcrop of a dyke of augite-diorite (diabase) with micropegmatite, whose microscopic characters have been described elsewhere.[1]

The hill which rises to about 200 feet above the alluvium near the village of Pammal, 2 miles west of Pallavaram, is composed principally of hornblende-augite norite (No. 9·673), with less hornblende in the central portions of the hill (9·676). On the western and north-western margin of the hill considerable quantities of biotite and quartz appear (9·675) sometimes with garnet (9·674). The rocks here include numerous veins of the acid forms, generally much coarser in grain than the average sample of norite.

The most interesting feature in this hill is the occurrence

[1] *Rec. Geol. Surv. Ind.*, Vol. XXX (1897), p. 31, *Quart. Journ. Geol. Soc.*, Vol. LIII (1897), p. 405.

of veins of pyroxenite, 3 to 5 feet wide, cutting through the norite.

Pyroxenite.

Although the pyroxenite dykes run in some cases parallel to the general direction of foliation, Dr. King and myself, whilst tracing one on the west side of the hill in September 1893, found it to distinctly ramify, one branch running westwards almost at right angles to the strike of foliation. The pyroxenites never show any chilled edges, so the fissures which they occupy must have been filled whilst the norites were still hot, and from the evidence of their occurring in distinct and ramifying dykes amongst this norite, they are probably part of the same series and derived from the same magma after the manner of some forms of Reyer's so-called *Schlierengänge.*

On a hill to the north-east of the Pallavaram railway station a 9-inch vein of hornblende pyroxenite (No. 9·667) in a hornblende-augite norite more completely displays the character of a *Schliere.* The vein is aligned parallel to the direction of foliation, that is, N.-N. E.—W.-S.-W.; and a section across its junction with the norite shows the ferro-magnesian silicates interlocking across the border (p. 164).

The rocks of St. Thomas' Mount and Pallavaram show a distinctly linear arrangement of their minerals in a N.-N.-E.—S.-S.-W or a N.-E.—S.-W. direction parallel, that is, to the adjoining

Foliation.

Coromandel coast-line. Although this linear arrangement of the constituent minerals has been referred to as "foliation", this term is generally used to imply the effects of dynamo-metamorphism developed to a much greater degree than has probably been the case with the charnockite series at Pallavaram. There is no evidence of the rocks having been folded since consolidation, and only local signs of their having been crushed. As pointed out in another section of this paper, it is probable that the linear arrangement of the minerals was probably induced during the process of consolidation, although of course it may have been accentuated in many, perhaps in most, exposures by continued exertion of the forces which determined the main physical conformation of South India in very early geological times.

Previous descriptions.

Many of the features presented by the rocks at Pallavaram and St. Thomas' Mount were noticed by Dr. P. M. Benza as long ago as 1836, who recorded an abundance of accurate information in his "Notes on the Geology of the Country between Madras and the Neilgherry Hills, *viâ* Bangalore and *viâ* Salem".[1] The garnetiferous rock, the trap-dykes, the decomposed, kaolinized form of the rock herein referred to as charnockite-pegmatite were noticed by Benza. The rocks forming the hills and here included in the charnockite series he speaks of as hornblende rock, and considered them to be overlying the fundamental granite.[2]

The rocks of St. Thomas' Mount and the Pallavaram Hills are referred to by Mr. R. B. Foote as "hornblendic gneiss of a very compact character," whilst the more acid forms of the charnockite series in this neighbourhood are spoken of as "quartzo-felspathic gneiss".[3]

THE SEVEN PAGODAS.

The Seven Pagodas.

Along the East Coast south of Madras, the crystalline rocks rise up like islands in the midst of the cultivated alluvium, the great prevalence of which reduces the value of the necessarily isolated geological observations. The only exposure of crystalline rock in the Chingelput District south of Pallavaram, which I have been able to examine carefully, occurs near the village of Mahavalipuram, or the Seven Pagodas (lat. 12° 36′ 55″; long. 80° 13′ 55″) which is 35 miles south of Madras and on the coast.

The Seven Pagodas are well known on account of the interesting rock-cut caves and temples, for the production of which nearly every exposure of rock for about two miles along the coast has been elaborately carved. The rock is referred to in Mr. Foote's memoir[4] as a "quartzo-felspathic gneiss" in which the

[1] *Madras Journ. Lit. Sci.*, Vol. IV (1836), pp. 1—27.

[2] For remarks by Capt. J. Allardyce, see section 12.

[3] *Mem. Geol. Surv. Ind.*, Vol. X, p. 127 (1871).

[4] *Op. cit.*, p. 127.

linear disposition of the constituents coincides with the direction of the exposed ridges as well as the coast line which runs a few degrees east of north to west of south. The petrological characters of the rock have been described on p. 146.

On the slight grounds of its resemblance in mineral composition to the coarse-grained quartz-felspar rocks associated with, and sometimes occurring as veins in, the charnockite of St. Thomas' Mount and Pallavaram, I have referred this rock to the charnockite series and have regarded the dirty white colours of its felspar as due to decomposition. In another section of this paper (p. 197), I have pointed out the differences between simple subaërial action (which in the compact charnockite series appears to be very limited in its effects) and the hydration, due possibly to submarine action, which extends to greater depths through the rocks. It is more likely that the low-lying rocks near the coast have been depressed more often and to greater depths than the higher portions of the hills and the rocks further inland, and if there really is the difference between the two kinds of decomposition—subaërial and submarine—such as I have imagined, it is not unnatural to expect that the low-lying crystalline rocks near the coast will be found to have lost the freshness which is so characteristic of the charnockite series in the Shevaroy and Nilgiri Hills for instance. Although the narrow fringes of marine beds lying near the east coast of Madras cover only a part of the land which has in past ages been depressed below the sea-level, the absence of all traces of marine deposits further inland justifies the conclusion that subaërial denudation has proceeded uninterruptedly for many geological ages on the high lands of the Madras Presidency.

South Arcot District.

The only detailed account of the distribution of the charnockite series in South Arcot District is due to Dr. H. Warth, who surveyed a portion of the district during the field-season 1894-95. Unfortunately no opportunity occurred for tracing out the relations

between the charnockite series and the remarkable rock which has been referred to by the older members of the survey as "the granitoid gneiss of South Arcot".[1]

This latter rock is distinguished by the white colour of its quartz and the inclusion of grains of pink felspar, accompanied by only a feeble development of gneissose and banded structures. Inclusions of hornblendic and micaceous gneiss and schist are extremely numerous and are often arranged with their planes of foliation at various angles to that of the imperfect foliation which the "granitoid gneiss" displays. So far these rocks agree with the granitoid gneisses which are so largely developed in the Hosur and Krishnagiri taluks of the Salem District; but their geological and petrological characters have not been studied sufficiently to justify more than a mere suggestion as to their correlation. The large tors and piles of loose blocks of this rock are very conspicuous along the Madras Railway at several points between Arkonam and Ulli stations, a distance of about 57 miles.

The specimens of the charnockite series collected by Dr. Warth in the South Arcot District belong to the "intermediate group," and their microscopic characters have already been described. As in other localities they form low, rounded hills isolated by stretches of alluvium which frustrate all attempts to trace out any character over more than very limited areas.[2]

SALEM DISTRICT.

Shevaroy Hills.

The most conspicuous exposure of this series of rocks in the Salem District forms the main mass of the Shevaroy hills, which cover an area of about 100 square miles, and form a mass 16 miles long from north-east to south-west and 10 miles wide from south-east to north-west. The highest portions exceed 5,000 feet above sea-level. The southern

[1] See King and Foote, *Mem. G. S. I.*, Vol. IV, p. 298, and Foote, *Mem. G. S. I.*, Vol. X, p. 129. Dr. Warth's report on this area has not been published.

[2] My attention was first called in 1892 to the existence of the charnockite series in South Arcot District by Mr. F. G. Brock-Fox, F.G.S., Executive Engineer, P. W. D., who collected specimens near Mailam, and from slides prepared by himself, recognised their resemblance to the rocks of Pallavaram.

flanks are precipitous cliffs, which give the hills a peculiarly massive appearance, but the valley of the Vániár, opening out to the north bisects the mass into two main lobes.

Messrs. King and Foote agreed with Dr. Benza in classifying the rocks of the Shevaroys as hornblende-schist.[1] Hornblende is generally a constituent—often a prominent constituent—of the charnockite series represented in these hills, and in the ultra-basic forms well-exposed near the foot of the ghât leading to Yercaud from the Suramangalam side, hornblende is so abundantly in excess of the hypersthene that the rock might be classified from hand specimens as an amphibolite. Sometimes small quantities of felspar occur, and so link these rocks with the norites (No. 9·114).

The main mass of the Shevaroy hills, however, is composed of "intermediate" members of the charnockite series comparatively free from garnets. Determination of the specific gravity of 48 specimens taken from different parts of the mass gave an average of 2·77 with closely agreeing results. In the prevalent intermediate variety there occur frequent examples of coarse-grained, acid contemporaneous veins, as well as basic, fine-grained, hornblendic schlieren (11·910, 11·911, 11·917). The basic schlieren are sometimes broken into irregularly shaped fragments which are cemented by more acid material, thus producing a kind of primary eruptive breccia. The much more recent dislocation-breccia of the so-called "trap-shotten" kind forms bands in several parts of the hills (11·909).

Sections taken from the Shevaroy rocks form good illustrations as a rule of the tendency which the ferro-magnesian silicates show to gather themselves into groups. Number 9,111, for instance, shows patches as basic as norite mixed with portions as acid as charnockite (compare slides 1,807 and 1,398).

All the rocks of the Shevaroys appear to be well schillerized, the blue quartz and blue-grey felspars being crowded with the hair-like inclusions described on p. 138, whilst the hypersthenes show the usual brown rods and plates. Microperthitic felspars are found in all specimens (Nos. 9,111, 112, 113, 692, 693, 694, 695, 696).

[1] *Mem. Geol. Surv. Ind.*, Vol. IV, p. 242.

A linear arrangement of the constituents, often accompanied by banding of an imperfect kind, is well displayed on weathered surfaces, and has been in some cases accentuated by slight crushing. The direction of foliation is very constantly N. E.—S. W. with a general dip of 50°-60° to the S. E. The mass is crossed from edge to edge by a dyke 50 yards wide of augite-diorite (diabase) with micropegmatite.

The scenery and physical features of the Shevaroys have been described by Messrs. King and Foote, and in the Salem District Manual by Mr. H. LeFanu. Like on many of these plateau masses of the charnockite series the gentle slopes of the wide valleys facilitate the artificial production of lakes of considerable dimensions. That at Yercaud, and the hills in the neighbourhood, are shown in plate XII which is the reproduction of a photograph taken from Arthur's Seat.

The Nagaramalai type.

Near the S.W. foot of the Shevaroys, and again between Salem town and Kanjamalai, small, bare, rocky hills stand up abruptly above the general level of the plain. Some of these show clearly their lenticular structure, and consist of masses of basic garnetiferous members of the charnockite series. The rocks are comparatively coarse in grain and sometimes contain garnets as large as one's fist. As a rule the only signs of foliation they show is an imperfect linear disposition of the constituents parallel to the long axes of the lenses and to the foliation of the gneisses around. Occasionally one comes across small E.N.E. dislocations in which a certain amount of mylonite is produced (see fig. 6)

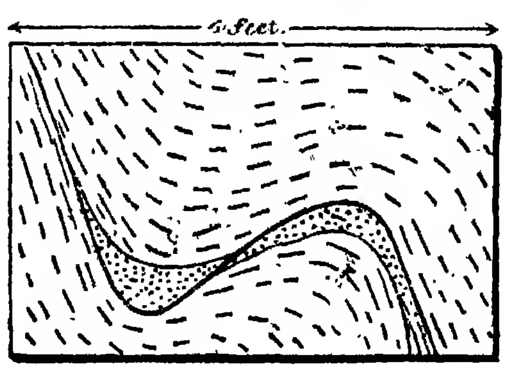

Fig 6. *Local twist with formation of mylonite in garnetiferous norite near Salem.*

and a local N.W. foliation. These garnetiferous types, of which Nagaramalai is a good example, are always accompanied by marginal lenses of pyroxenite (pyroxene-rocks) which often contain small quantities of olivine and hercynite. The minerals of these rocks in the immediate neighbourhood of the Chalk hills are always well schillerized and the garnets contain strongly bi-refringent needles whose characters and regular crystallographic disposition have been described in a separate paper.[1]

Other masses of the basic varieties (norites) without garnets occur as lenses of all sizes in the "leaf gneisses" of the Salem-Ahtúr valley. They resemble very closely in mineral composition and structure the basic schlieren in the Shevaroys (11·918, 11·923).

"Chalk Hills."

The members of the charnockite series cropping up between the two main magnesite-producing areas of the Chalk hills form interesting examples of alteration by the action of the peridotites intruded into them. The fresh appearance and the blue colour of the normal rock has been changed to a dirty white. This change of colour is seen under the microscope to be due to the development in the felspars of an innumerable number of minute black dots arranged in rows parallel to the twin planes (plate VIII, fig. 5). The action has, however, been apparently confined to the felspars; for the quartz, hypersthene and iron ores appear to be unaltered (No. 9·689). The change in the felspars is not unlike that which in the neighbourhood of the Giridih coalfield of Bengal appears to be the preliminary form of static metamorphism which on dynamic action results in the production of scapolite.[2]

Tongues of charnockite corroding the older biotite gneiss are exposed $3\frac{1}{2}$ miles south of Salem on the Namakal road; these are described in another section of this memoir (p. 226). The dislocation breccias or so-called "trap shotten" bands are also described in a

[1] Holland, "On the acicular inclusions in Indian garnets." *Rec. Geol. Surv. Ind.*, Vol. XXIX, 1896, p. 16.

[2] *Cf.* Holland and Saise, "On the igneous rocks of the Giridih (Karharbari) coalfield and their contact effects." *Rec. Geol. Surv. Ind.*, Vol. XXVII (1895), p. 123.

special section and further details of the geology of the immediate neighbourhood of Salem will be published in a separate memoir.

The charnockite series are represented in other hill masses in the Salem District, for instance in the Javadis and in the Dharmapuri Hills. In the Dharmapuri taluk corundum occurs, with sillimanite, rutile, biotite and cryptoperthite, as constituents of large ellipsoidal inclusions near the junction of the charnockite series with a biotite granite which occurs in large quantities in this taluk and that of Hosur. As the Salem and Coimbatore Districts are now being carefully surveyed, it is advisable to postpone further discussion of the local geological relations of the charnockite series until they have been worked out in greater detail.

COIMBATORE DISTRICT.

The charnockite series exposed in various parts of the Coimbatore District will be described by Mr. Middlemiss, who has been surveying this area for some four years. But one instance illustrating the amphibolization as well as one of the ways in which banding is produced, should be referred to at once. Near Tirrupur railway station there are considerable exposures of hornblendic gneisses along the banks of the Noyal river, which, on microscopic examination, are found to contain hypersthene, and in other ways to repeat the essential features of the charnockite series. As sections shew various stages in the amphibolization of the pyroxene with consequent production of green hornblende, the unusually large quantity of the latter mineral is satisfactorily accounted for. Garnets, more often than hornblende, are found amongst the products of the alteration of pyroxene in the South Indian charnockites, but it now seems likely that, whilst the unstable pyroxene may give rise to garnet at high temperatures, hornblende is the more usual result of change at lower temperatures. It is thus likely that one of these minerals may characterise one area or one mass which happens to be deeply buried, whilst the other may arise when the rock becomes deformed nearer the surface.

Hornblendic forms near Tirrupur.

The other feature of interest displayed near Tirrupur is the production of banding by *lit-par-lit* injection of the non-felspathic forms along the foliation planes of the basic types. That this is the correct explanation of the well marked banding in this neighbourhood is shown by the fact that the non-felspathic "bands" sometimes break across the foliation planes, and sometimes actually bifurcate (see plate IX). The ultra-basic (non-felspathic) bands often weather with formation of onion-like shells and with deposition of calcareous kankar along the cracks. A good case is badly represented in the photograph forming plate X.

The charnockite series here, as they often are, are associated with quartz iron-ore beds, and in other parts of the same district also with crystalline limestones.

NILGIRIS.

The civil district of the Nilgiris, which is very nearly coincident with the hill ranges known as the Nilgiris and Kundas, is practically made up of members of the charnockite series. The plateau, which forms such a conspicuous feature in the south of India, measures 42 miles long and 15 miles broad, covering an area of about 750 square miles. In a large number of places it exceeds 8,000 feet in height, and attains its maximum altitude of 8,760 feet in Dodabetta, a rounded hill near Ootacamund (lat. 11° 24′ 5·40″; long. 76° 46′ 44·39″).

The characteristic scenery of a charnockite area is typically developed in the Nilgiri Hills. The rounded peaks and grass-covered undulating "downs" of the plateau are features characteristic of a country in which the inequalities developed by uninterrupted weathering have completely obliterated all the physical features originally formed by earth-movements. The scenery of the Nilgiris contrasts very strikingly with the deep narrow gorges of the Himalayas, where the rapid erosion, following the geologically recent elevation of the mountain range, has left the slopes so near the angle of repose of the broken rock, that landslips

are of daily occurrence, whilst the vegetation is only allowed an insecure and temporary place for development in places where, by local accident, the slope is comparatively gentle. In the Nilgiris the slopes are clothed with thick turf, and the valley "bottoms" often covered with deep peat bogs.

Weathering.

In consequence of this protection from rapid erosive action the weathering of the rocks has gone on by simple decomposition *in situ* to depths often of 40 or 50 feet. Road cuttings through this decomposed material show the average products to be a soft, yellow or red clay, in which, on account of the variations in original composition, the basic portions can, though reduced to a mere clay, be easily distinguished from the acid contemporaneous veins which contain more pure kaolin and are seen to ramify in all directions through the rock. Often in a neatly cut slope of this clay small local faultings are beautifully displayed with diagrammatic clearness.

In the midst of this deep covering of decomposition products, rounded boulders of the fresh rock are frequently found without any apparent regularity of relation to their depth from the surface. The onion-like shells of partially decomposed material around these boulders are seldom more than a few inches thick, so the passage from the pure clay to the fresh rock is remarkably rapid. It is to this interesting feature that I have referred as an illustration of the differences between the decomposition produced in rocks exposed to the action of unaided atmospheric agents, and the alteration noticeable in rocks which have been depressed below the sea level and submitted to the corrosive action of water charged with carbonic acid and salts acting under pressure (*vide* p. 197). Sections taken from the rock of the Nilgiris within a few inches of the clay decomposition products are seen, on microscopic examination, to be most remarkably fresh, the felspars being perfectly clear and free from kaolinization. The same thing is true of the olivine-crystals in the norite dykes which cut through the charnockite series in the same area. Even in small boulders olivine-crystals are generally without the slightest signs of

serpentinization, although the dykes are converted into a yellow clay where they come to the surface.

South-eastern face of the mass.

The south-eastern face of the Nilgiris is a steep, precipitous scarp with an average direction of E.-N.-E.—W.-S.-W., which is the direction also of foliation in the hill. The rocks are much more definitely foliated near this face than further towards the centre of the plateau, and the foliation is accompanied by a considerable development of garnets. In the neighbourhood of Coonoor the marked foliation and the great development of garnets (see No. 9·307) are especially noticeable. It appears to me to be in keeping with the few geological data available to regard this great southern scarp as approximately coincident with the original limits of the mass in this particular area, just as the corresponding southern scarp of the Shevaroys is possibly a corresponding line limiting that particular intrusion. In any earth movements which may have taken place, it is natural to expect the great, solid masses of compact rock forming the Nilgiris to sever connection with the very different material which forms the schists and gneisses of the Coimbatore plains, and this southern scarp probably, therefore, now indicates also the direction of a great fault plane. Naturally the weather has scored out many deep marks in this southern face and considerably modified its original outlines; but the sides are still more precipitous than one would expect as the simple result of differential denudation. In a separate memoir the evidences for a similar state of affairs will be detailed for the Shevaroy Hills (*Mem. Geol. Surv. Ind.*, Vol. XXX, part 2).

Pegmatoidal pyroxene plagioclase rocks.

One of the most interesting features in connection with this southern margin of the Nilgiri mass is the occurrence of large, lenticular inclusions of heavy, basic, pyroxenic rocks of a very peculiar type. The lenticles are often as much as 15 feet long and 5 feet across; they are disposed in bands parallel to the foliation of the charnockite series in which they are included, and are sometimes cut through, like the charnockites themselves, by the narrow dykes of olivine norite,

such as occur, for instance, in the river-bed below the Coonoor bridge.

The inclusions referred to are formed of extremely tough rocks, with a specific gravity varying between 3·13 and 3·25. They often exhibit a remarkable lustre-mottling due to the development of pyroxene crystals measuring sometimes six inches across. Under the microscope thin sections of the pyroxene are quite colourless and appear to be changing into a peculiar pale-yellow hornblende. Eyes of clear plagioclase occur enclosed in the pyroxene, and as several apparently isolated sections of this plagioclase show simultaneous extinction, they are probably in crystallographic continuity with one another (No. 9·302). The structure is, therefore, due, not to ophitic development of the pyroxene, but to a pegmatoidal intergrowth of the two minerals. Sometimes the pegmatoidal structure is destroyed and the rock becomes granulitic (No. 8·760). Much of the pyroxene is rhombic and in thick sections shows a very faint pleochroism. The hornblende shows its characteristic prismatic cleavage which facilitates the determination of its optical properties. The extinction angle is 18° ($c : \mathfrak{c}$). The pleochroism is well marked though not so strong as in common hornblende—

$\mathfrak{a}$ = very pale yellow.

$\mathfrak{b}$ = brown-yellow.

$\mathfrak{c}$ = yellow.

The optical properties of this mineral agree with those of the 3rd variety of hornblende in Lacroix's "pyroxenic gneiss *b*" (*Rec. Geol. Surv. Ind.*, Vol. XXIV, page 182), which was likewise found in a rock with pegmatoidal pyroxene and felspar. Unfortunately, however, Lacroix has given no hint as to the geological relations of the rocks described, so this partial agreement in microscopic characters might be purely fortuitous.

The biotite which invariably occurs in these inclusions is a highly pleochroic variety varying from deep yellow-brown to very pale yellow. Flakes examined in convergent polarized light show a narrow optic axial angle with a negative bisectrix. Neither free

iron-ores nor garnets have been observed in the peculiar lenticular inclusions, although they are abundant enough in the associated ordinary members of the charnockite series.

At present I am unable to recall any precise parallel for these peculiar inclusions. Their lenticular shape and their occurrence in trains along the same band of the charnockite series suggests that the lenticular shape is the result of the "pinching" of a once continuous band. The conversion of a band of tough basic rock into lenticles, instead of the mere spreading out of the constituents into a thinner band, illustrates very prettily the various degrees by which different rocks yield under pressure. As a general rule the more basic rocks are, under pressure, less plastic than acid ones and so take on simple foliation less readily; it is in consequence of this fact, Adams thinks, that basic masses are so frequently found in trains of fragments included in thinly foliated siliceous forms instead of forming thin basic leaves.[1]

Western margin of the mass.

The western margin of the Nilgiri mass appears to be as precipitous as the southern; but in the north it slopes away through the portion known as the Nídumalai range till it reaches the lower-lying plateau of the Mysore State. In the Wainád to the north-west and in Malabar on the west the average strike of the foliated rocks is N.-N.-W.—S.-S.-E., but we have no details as to the connection between the physical geology and the change of strike which probably occurs near the line of junction between the Nilgiri mass and the gneisses of the Wainád and Malabar. The disturbances recorded by Dr. W. King [2] in the former locality, and those described by Mr. Lake in the Malabar District,[3] would be of much greater interest if we possessed more precise data than is obtainable from a mere macroscopic description of the rocks. The interesting questions connected with the geological relations of the Nilgiris to the surrounding low countries must, therefore, be left for a while in this incomplete condition.

[1] See *Amer. Journ. Sci.*, Vol. L (1895), p. 62.
[2] *Rec. Geol. Surv. Ind.*, Vol. VIII, p. 37.
[3] *Mem. Geol. Surv. Ind.*, Vol. XXIV, plate II.

Schlieren.

Another feature of interest in connection with the charnockite series in the Nilgiri Hills is the frequent display of basic *schlieren* of norites within masses of more acid composition, and, what is strictly analogous to this phenomenon, numerous veins of the acid variety running through the basic portions after the manner of the so-called "contemporaneous veins."

According to the relative abundance of the basic and the acid varieties of the same series, we may have, either the basic rock occurring as small islands in an acid matrix, or the latter may occur only as small veins cutting through, and subordinate in quantity to, the former.

Primary breccia.

Perhaps the most interesting case is that in which the acid and basic varieties occur together in about equal proportions, and a very interesting example of such has been exposed on the roadside under the Convent and near the Boat House of the Gymkhana Club in Ootacamund.

In this pretty instance the basic fragments are scattered through an acid matrix to form a pseudo-breccia; but the linear disposition of the angular, inequiaxed fragments of basic rock, as well as of the acid material in which they lie, indicates the direction of flow previous to consolidation. We have thus a case of what the late G. H. Williams called *protoclastic* structure in imitation of Lossen's term *Primärtrümer*, and of Sederholm's terms, *Primärbreccia* and *Eruptivbreccia* (see fig. 7, and p. 218).

COORG.

The Western Ghâts.

The charnockite series occur on the west of Coorg, where they constitute the Western Ghât ridge, and again on the east, where a large mass, and perhaps several smaller ones grouped around, form lenses, which locally appear as bands, in the biotite gneiss. The direction of foliation is very constantly N.-W.—S.-E. or thereabouts. The former exposures run south-eastwards into the Wainád and probably join up with the Nilgiri mass. The eastern margin of these rocks is quartzose and

highly garnetiferous as well as graphitic ; it is along this band of peculiar rocks that the charnockite series march with the Mercara group of gneisses and schists, and the phenomena here displayed are regarded by Dr. Walker and myself to be due to contact metamorphism, though it is difficult to decide the exact boundary line between the two great formations and so distinguish endogenous from exogenous products.

Dykes.

The chief feature of interest in connection with the eastern occurrence in Coorg is the frequent display of narrow bands of basic charnockites in the biotite-gneiss. Careful examination of these has revealed the curious fact that they all possess fine-grained basic and hornblendic selvages which are almost certainly the result of chilling at the margins. These bands must, therefore, be regarded as dykes intruded into the older biotite-gneiss. They vary very greatly in width, sometimes being merely a few inches in thickness and at other times swelling out to large masses. Several of these are very clearly exposed in the bed of the Cauvery at Fraserpet (see plate XIII). In their mineral composition and structure they display the essential features which characterise the charnockite series and like them often contain garnets (Nos. 12·395 to 12·405). Their association with larger masses of the more normal types leaves little doubt about the conclusion that these dykes are true members of the charnockite series and under the circumstances must be regarded as strong evidence in favour of the conclusion that these rocks are igneous in origin and intrusive in their relations to the older gneisses.

MADURA AND TINNEVELLI.

Palni Hills.

In the Palni Hills we have a mass of the charnockite series, as large as that of the Nilgiris. The Palni mass is 54 miles long from east to west and 15 miles broad; including Anjinad, it covers 798 square miles. The plateau is at an average elevation of 7,000 feet above the sea, and is characterized by scenery similar to that on the Nilgiris. In all the hill masses composed of the charnockite series the gentle

undulations of the plateaux facilitate the production of lakes of considerable dimensions with very slight artificial assistance. At Ootacamund on the Nilgiris, at Yercaud on the Shevaroys, at Kodaikanal on the Palnis, and at Neuralia and Kandy in Ceylon, lakes of considerable size have been formed by taking advantage of the facilities offered by the gently undulating surfaces of the plateaux formed of the rocks which are grouped together in this series.

The Palnis are physically connected with the Anaimalais and are probably also geologically a continuation of these hills; but this area lies principally in the Coimbatore District and is only now in the course of being surveyed.

Our principal information concerning the distribution of this series in the remaining portions of Madura and Tinnevelli is due to Mr. R. B. Foote,[1] who described the leading member of the series as a "granitoid gneiss", which, from its occurrence near Cape Comorin, was designated the "Cape Comorin type" (*Op. cit.*, p. 28).

Cape Comorin type of gneiss.

The "Cape Comorin granitoid gneiss" appears to be interbanded with granular quartz rock, and in the Madura district these rocks, according to Mr. Foote, form six distinct groups, associated in a few places with coccolitic marbles. In the Tinnevelli District both the granular quartz rock and the crystalline limestone are found again in association with the Cape Comorin type of granitoid gneiss.

Many of the prominent hills in these two southern districts are composed of the charnockite series ("Cape Comorin type of granitoid gneiss"). The southern ghâts, which are partly included in the State of Travancore, are practically composed of these rocks, Mahendragiri, the most southerly of the great peaks of the range, being a noteworthy example, attaining an altitude of 5,419 feet.[2]

[1] *Mem. Geol. Surv. Ind.*, Vol. XX, p. 1.

[2] For further details concerning the crystalline rocks of Travancore see W. King, *Rec. Geol. Surv. Ind.*, Vol. XV, p. 87, and Foote, *Ibid*, Vol. XVI, p. 20.

CHAPTER VI.

General Considerations.

On account of the large are acovered by the charnockite series in the southern portion of the Madras Presidency, the predominant features which they present must necessarily affect our generalisations concerning South Indian petrography and geology.

Four such points considered below deserve special mention :—

(1) The abundance of magnesian minerals.

(2) The preservation of old pyroxenic rocks.

(3) The limited amount of hydration suffered by the rock-constituents.

(4) The nature of the so-called "trap-shotten" gneiss.

Abundance of Magnesian Minerals.

The most remarkable feature which has been revealed by recent microscopic study of the crystalline rocks in South India is the very great predominance of the pyroxenes (and especially of the rhombic forms of that group) amongst the ferro-magnesian silicates. In addition to the series described in this paper, which is probably the most abundant of all the rock-groups in the southern portion of Peninsular India, and in every variety of which hypersthene is a constant and characteristic constituent, the central and eastern parts of the Madras Presidency are cut through by an enormous number of basic dykes, in which rhombic pyroxene also is a leading mineral. Judging thus by the mineralogical composition of the rocks, which is confirmed by the few chemical analyses that have so far been made, the bases magnesia and ferrous oxide must take an unusually prominent place amongst the chemical constituents of the southern portions of the Peninsula. Besides

occurring as a constituent of the enstatites, which are so widely distributed through the Madras rocks, magnesia occurs even in larger proportions in the peridodites, which, either as dunites, saxonites, picrites or their decomposed forms magnesite, serpentine and steatite, are now known to be far more abundant than was suspected at the time of the first recognition of these highly magnesian, ultra-basic rocks near Salem in 1892.

Prevalence of Pyroxene.

More remarkable than the prevalence of magnesian compounds is great predominance of the pyroxenes amongst the rock-forming minerals of the south. The pyroxenes are essential constituents of the charnockite series which make up the chief mountain masses and cover large areas in the low-lands; they characterise the basic dykes which cut the older crystalline rocks in all directions, and the soda-bearing members of the group have recently been found in the augite-syenites of the Yelagiri hills and associated intrusives.

These are all geologically old rocks, probably not later than lower palæozoic in any case, and the perfect preservation of such unstable minerals as the pyroxenes forms an interesting corroboration of now established conclusions as to the long quiescence of Peninsular India, a geological quiescence which was inferred by the older geological surveyors from stratigraphical evidence alone.

Although the dyke-rocks of supposed Cuddapah age are preserved with perfect freshness, there is abundant evidence to show that the previously formed Dharwars suffered from dynamo-metamorphism, and the pyroxenic dykes and flows of the earlier period have been largely changed to hornblendic schists.

Knowledge of the profound dynamo-metamorphism suffered by the Dharwar transition rocks, naturally provokes a search for evidences of similar action on the associated and presumably older Archæan formations in the same area; and here the enquiry

comes home to us, for the charnockite series are assumed to be Archæan.

Before this enquiry can be satisfactorily undertaken there are several points on which further information is essential. In the first place, the lower limit of the Dharwars is not sufficiently defined to warrant the assumption that all the Dharwars are younger than all the Archæan gneisses and schists. In other words, the break between the biotite gneisses and the Dharwar rocks, which Mr. Foote recognised in the Bellary District, has only a local value.[1] No unconformity has so far been found between the charnockite series and the Dharwars. On the other hand, members of the charnockite series occur as lenticular masses or bands associated with ferruginous quartzites which do not differ greatly from the ferruginous quartzites so abundant in the lower stages of the Dharwar system. The ferruginous quartzites referred to are those which occur so frequently in the central and southern districts of the Madras Presidency, Kanjamalai and Godamalai being conspicuous and well known examples in the Salem District for instance; these rocks are composed of magnetite, hematite, and quartz with a pale-green hornblende, and they only differ from the rocks of similar mineral composition in typical Dharwar areas in their more perfect crystallization and in, perhaps, the predominance of magnetite over hematite—points which merely indicate differences in degree of metamorphism, not necessarily differences of age.[2] As far as these magnetic iron-ore beds are concerned, there is not the slightest reason for considering them to be younger than the charnockite series. On the contrary, if our views as to the origin of the charnockite series are sound, it is more likely that the latter are younger and have attained their present

[1] Manual of Geology of India, 2nd edition, pp. 49, 50; R. B. Foote: "The Geology of the Bellar District," *Mem. Geol. Surv. Ind.*, Vol. XXV (1895), pp. 28, 74.

[2] The suggestion that these southerly iron-ore beds are merely altered outliers of Dharwar age has been made in a separate memoir descriptive of the rocks in the immediate neighbourhood of Salem (*Mem. Geol. Surv. Ind.*, Vol. XXX, part 2). The discovery of large proportions of hematite in the magnetic ores of the south and of magnetite in hematitic ores of the Dharwars considerably reduce the previously recognised differences between the two groups of rocks.

position by intrusion. Even if we reverted to the old idea that all these rocks are regionally metamorphosed sediments, the interbanded charnockites could not be older than the magnetic iron-ore beds, for the latter occur below as well as above the former.

Unfortunately, the question of greatest importance—the petrology of the Dharwar conglomerates—is the subject about which we are still most ignorant. Pebbles of "schist, quartz, quartzite, grit, banded hornstone and gneiss" have been referred to in connection with these conglomerates, but their microscopic characters have not been described. Recently, through the kindness of Dr. J. W. Evans, State Geologist of Mysore, we received pebbles from a Dharwar conglomerate which occurs in the Kolar Goldfield. Microscopic examination of these shows them to be indistinguishable from the old biotite-gneiss which is corroded by tongues of the charnockite series near Salem (*vide infra*, p. 226). From these facts we conclude that the charnockite and the particular Dharwar conglomerate from which these pebbles were obtained are both younger than the biotite-gneiss near Salem, but we still have no clue as to the relative ages of the Dharwars and the charnockites. It is to be hoped that every effort will be made in future to collect and identify pebbles from the lower Dharwar conglomerates with a view to the elucidation of this important point.

Although we have no clear proof of their antiquity, we must be prepared for the conclusion that the charnockites are quite old enough to have suffered from the tangential pressures which have left their mark so plainly on the highly folded Dharwar strata. Under such circumstances, the preservation of so much pyroxene would require explanation.

Stability of pyroxene at high temperatures.

Concerning the anorthosites of Canada, which have much in common with some forms of the charnockite series, Adams has made some very suggestive remarks about the stability of the pyroxene during the granulation which is sometimes carried far enough to produce a thorough "Rutschmehl." "The cataclastic structure is not," Adams says, "developed

along certain lines, but may be observed more or less distinctly throughout the rocks. Where it occurs there is neither saussurite nor uralite—although the granulation of the pyroxene may be carried so far that only the smallest remnants of the original individuals remain." From this, as part of the evidence, he concludes that "these movements probably took place when the rock was still so far beneath the surface of the earth and so weighted down by the overlying rocks that breaking and shearing with the movement of the resulting masses was impossible. Such a motion would present certain resemblances to that of a very tough pasty mass ....while the rock was still very hot and perhaps even near its melting point. This would explain why pyroxene, which, according to the experiments of Fouqué and Michel-Lévy, represents the stable form at a high temperature, is not changed into amphibole which represents the more stable form at a low temperature.[1]"

All these remarks are applicable too to the charnockite series, and with regard to the last point it is not unlikely that the great prevalence of pyroxenic rocks in these old protaxes, like Canada and Madras, where denudation has proceeded uninterruptedly for such long ages, is due to the exposure of relatively low portions of the earth's crust, lower portions comparatively than those which have been protected by sedimentary coats, and low enough to permit such a regional rise of temperature that the pyroxenes, for instance, are crushed without amphibolization.

The prevalence of garnets in some members of the charnockite series which show no signs of dynamo-metamorphism, suggests that although the pyroxene is the stable form near fusion point and hornblende the stable form of the same compound at low temperatures, there is an intermediate, but high, temperature, short of fusion, at which either hornblende or pyroxene breaks

[1] Adams. "Report on the Geology of a portion of the Laurentian area lying to the north of the Island of Montreal." *Annual Report of the Geol. Surv. Canada*, Vol. VIII (1896), part J, pp. 114 and 115. There are many interesting points of resemblance between the old Canadian protaxis which has been exposed to continuous denudation since Potsdam days and that of Madras.

up into a more basic garnet and a more silicious bye-product, quartz or felspar—a kind of liquation process facilitating the segregation of basic and acid extremes from a body of intermediate composition. It is to such a cause that the prevalence of garnets in these old pyroxenic rocks should be ascribed.

The means by which the pyroxenic and garnetiferous rocks have been brought to the surface have been in action for long geological ages, during which Peninsular India has suffered from no serious earth-movements. The deep-seated rocks have thus been brought to the surface without undergoing any form of crushing at intermediate levels, and so the original characters of our charnockite series are probably preserved in an unusually perfect manner.

Limited degree of Hydration.

Besides the freedom from crushing due to absence of earth-movements since Cuddapah times, the peninsular rocks have escaped general hydration in a most remarkable way. The freshness of South Indian rocks is not confined to the charnockite series: the olivines in the basic dykes of Cuddapah age scarcely ever show a sign of serpentinization, and even in the large number of dunite areas serpentine occurs only in small quantity.[1]

Another striking example is offered by the elæolite-syenites recently discovered in the Coimbatore District, where the mineral elæolite, quite as susceptible to hydration as olivine, has been preserved in a perfectly fresh condition although the rock is probably as old as any sedimentary formation in South India, and was even described as a member of the crystalline schists.

And yet these rocks, which are internally so remarkably fresh, are, in common with all rocks exposed to the moist, warm climate of tropical countries, changed near the surface into a soft clay to depths of 50 feet or more. Near Coonoor in the Nilgiri Hills both

[1] Dunites and other peridotites of South India are frequently changed in large quantities to magnesite. In another paper reasons are given for ascribing this change to the deep-seated action of carbonic acid and not to subaërial agencies.

the charnockites and the olivine-norite dykes are changed to considerable depths into a red or yellow clay, and yet when the clay is removed and the hard rock revealed, a microscopic section taken from quite close to the weathered surface shows that even such a susceptible mineral as olivine scarcely ever shows any signs of alteration to serpentine (see Nos. 11·350, 11·351, 11·353, 11·356). It seems therefore, that mere subaërial action is insufficient to account for the marked hydration which olivine generally shows in rocks that are not quite recently formed, and the only reason for accounting for the remarkable freshness with which our South Indian rocks have been preserved since lower palæozoic times is based on the fact that they have not been depressed below the sea-level. The action of water would naturally be accentuated by the greatly increased pressure following depression below the sea, and the action of the water itself would be accentuated by the presence in solution of carbonic acid and salts of lime, magnesia aud the alkalies. Except for narrow marginal portions along the coast, we have no evidence of any great changes of level in South India since Cuddapah times, and it is extremely unlikely that the central portions of the Madras Presidency have, since that time, been depressed below the sea-level. Our rocks have, therefore, been exposed in all probability to undisturbed subaërial action for many geological ages. Peridotites occurring in other parts of India — the Andamans, Burma and the North-West Himalayas — which have been submerged below the sea in Tertiary times, are, like the common instances in Europe, largely changed to serpentine, and although there may be some other reason for such hydro-metamorphism, the only apparent difference between Peninsular India and the other areas lies in the circumstance that the former area has not been subject to submarine conditions.

"Trap-shotten" gneiss.

Messrs. King and Foote were the first to recognise this peculiar phenomenon, which is now known in several exposures of

the Salem gneisses. On the supposition that the black compact strings and shreds were due to injected basic trap they suggested the name "trap-shotten gneiss[1]."

Microscopic examination of the rocks, however, does not offer evidence in support of this theory, although, judging from macroscopic characters alone, the conclusion is a most natural one. In the first place, the black substance possesses none of the peculiar microscopic structures which characterise "trap" or any substance which has resulted by direct consolidation from thorough fusion; it is, on the other hand, composed of a black dust, through which angular fragments of quartz and other transparent minerals are disseminated, and the whole rock is highly crushed, with the production of mylonite and frequent microscopic faulting of the constituents. Very often this brecciation is quite evident in the field and is accompanied by a well-marked "strain-slip" cleavage in the neighbouring rocks. In fact, the phenomenon is essentially a form of brecciation due to dislocation of the rocks along definite lines.

But the production of the strings and tongues of compact, black mylonite is a peculiarity for which I can recall no exact parallel amongst crush phenomena; for the rocks are often acid in composition and that at first makes the black colour of the mylonite a matter of considerable surprise. Careful exmination by the microscope shows that where the quartz crystals have been smashed and granulated, the granular bands often include innumerable minute opaque, black bodies which suggest either sublimation by heat or introduction of material in solution. Herein comes the significance of King and Foote's observation that the so-called trap-shotten phenomena are accompanied occasionally by true trap-dykes. Where trap-dykes are actually associated with this structure it is possible that compounds may have been sublimated into the adjoining breccia; but it is quite certain that the black substance is not a bodily injection of molten material: the black material has essentially the microscopic structure of an indurated dust, never that of a

[1] *Op. cit.*, p. 271.

rock cooled from fusion. Besides, the structure is more often found well beyond the range of any known trap-dyke.

In some cases examination of very thin sections with a one-tenth inch objective reveals the beginnings of an internal crystal organization in the black dust; but they are no more definite than may often be seen in an indurated volcanic ash, and never of the nature of a microlitic igneous matrix. The transparent fragments lying in the black dust have generally the characters of quartz, all traces of the felspars having in general been utterly destroyed. When members of the charnockite series display this "trap-shotten" aspect, microscopic examination of the fragments forming the breccia often shows actinolitic fringes (similar to the so-called "reaction rims") around the hypersthenes, a phenomenon seldom exhibited in the normal rock. Sometimes shallow bays in the quartz crystals are filled with the black dust as if corrosion had commenced. Several such phenomena indicate that the breccia has been highly heated, but nevertheless not to a temperature sufficient to completely fuse the dust. To check this idea experimentally, I crushed a specimen of charnockite and heated the rough powder in a furnace to a white heat, sufficient to produce a very imperfect fusion; the result was a fritted black cake having the lustre of a tachylyte and showing in thin sections a black structureless matrix including angular fragments of quartz; in fact, the fritted charnockite powder very closely resembled the so-called strings of "trap" in these breccia bands.

The mere heating of the charnockite dust—and in this experiment the acid form was used—is thus evidently sufficient to account for the black colour of the mylonite in the breccia without any question of introducing material from without.

The source of the heat which has indurated and blackened the mylonite is then the only question left. The fact that there are numerous instances of these "trap-shotten" bands well beyond the range of intrusive dykes shows that the presence of the latter is not essential; and the perfectly unaltered condition of the rocks in the neighbourhood of the brecciation bands shows that the effects of the

heat are not general, but are confined to the bands themselves. These facts narrow the issue to the very natural inference that the heat was produced by the process of brecciation itself, which was probably of a much more violent nature than that which produces the commoner and more general phenomena of dymano-metamorphism.

When such deformities as eye-structure, mortar-structure and peripheral granulation of the constituents result from dynamo-metamorphism, the whole, or a large portion, of the rock mass suffers, and the disturbance being more general, the temperature rises only to a limited degree. There are also good reasons for concluding that a general deformation of all the constituents of a rock indicates a gradual and slow application of the dynamo-metamorphic agencies. In these cases, therefore, where the rock has smashed along a particular band or line, the local rise of temperature resulting from the heat of friction is likely to be excessive; first, because of the limited area to which the disturbance is confined, and secondly, because this gives a *primâ facie* reason for supposing that the disturbance must have been unusually violent.

Briefly, it is concluded that this peculiar phenomenon is the direct result of brecciation, and is not due to actual injection of trap; the black colour and indurated nature of the mylonite (which is outwardly so tachylytic in appearance) are probably the result of the heat produced during the violent brecciation of the rock by which a temperature sufficient to frit the mylonite, but insufficient to melt the rock, was produced.

The geographical distribution of this peculiar breccia and the direction of the bands will probably prove to be of some geological interest; but so far all the cases which have been recorded occur within the district of Salem. Messrs. King and Foote called attention to the fact that the bands often resist the weather more effectually than the surrounding unaltered rocks, and so stand up as well-marked ridges. Besides the case they refer to near Ahtur, a very striking instance is exhibited at about half a mile north-east of Kagankarai in the Tirupatur Taluk, running, like the Ahtur ridge,

north-by-east for at least 6 miles. The Kagankarai ridge is very nearly in line with that near Ahtur, and as an example of the breccia is exposed at an intermediate point (south-west of Mankunju hill), further examination along the line should be made. Other examples of the brecciation bands occur near Munakhal and Mallur, 8 miles south of Salem; on the western spur of the Jarugamalais, near the Namakal-Salem road; 3 miles south of the latter place, and further south on the western side of the same road; south of the Gundur spur of the Shevaroys, as well as in the Shevaroy mass itself, 2 miles north of Yercaud. Similar phenomena have recently been observed by Mr. Hayden and myself in the Monghyr district where the mylonised bands are bordered by more pronounced strain-slip cleavage, and the mylonite itself shows less signs of having been raised in temperature; it is hardened but not blackened.

PART II.

ORIGIN OF THE CHARNOCKITE SERIES.

In investigating the origin of the charnockite series one naturally considers first of all those conclusions which have been established for the previously known foreign relatives of the rocks; for what has been established about them will form the first working hypothesis for indicating the lines of most profitable research amongst the Madras occurrences. This part of the paper is consequently devoted, firstly, to a brief discussion of the affinities shown by the charnockite series to foreign types, and secondly, to a summary of the evidences obtained so far by field work in the Madras Presidency.

CHAPTER VII.

CORRELATION WITH FOREIGN RÖCKS.

(1) *Comparison with the "Pyroxene-granulites."*

The Saxon granulite area.

Rocks of this nature have been found to have a wide distribution as members of the Archæan crystallines, and their mode of origin has formed the subject of much discussion. Naumann[1] considered the Saxon granulites to be eruptive in origin, and J. Lehmann, in his great work *Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine*, brought forward an abundance of evidence to show that the granulites and pyroxene granulites had consolidated like granitic rocks at great depths and assumed their present gneissose structure on account of the pressures caused by ancient sediments; and thus in a modified sense, Lehmann confirmed the conclusion of Naumann. But between the date of the publication of Naumann's papers (which only supported with more detailed evidence the conclusions originally stated by Weiss in the commencement of the century) and the appearance of Lehmann's memoir in 1884, various contradictory views were expressed concerning the Saxon granulites and pyroxene-granulites as well as about the similar rocks in Bohemia, Bavaria, Austria and Scandinavia. In all these cases, however, the pyroxene granulites appear to have been regarded as members of the Archæan crystalline series, and none of them has been found to be intrusive into rocks of undoubtedly sedimentary origin.

Canadian pyroxene-granulites.

Whilst admitting that the evidence is too incomplete to permit a definite conclusion, Adams has described some occurrences of pyroxene-granulites in Canada which suggest their igneous origin.[2] The pyroxene-granulites of the area described by Adams differ

[1] Lehrbuch d. Geognosie, Vol. II, p. 184.

[2] "Report on the Geology of a portion of the Laurentian area lying to the north of the Island of Montreal." *Ann. Rept. Geol. Surv. Canada* (1896), Vol. VIII, Part J.

from those of Saxony chiefly in being a little coarser in grain, and in possessing, as a general rule, a more or less indistinct schistose structure, whilst garnet is less abundant. In these points the Canadian pyroxene-granulites agree with many occurrences in South India. In one case Adams has figured a dyke-like arm protruding into the leaf-gneisses from the pyroxene-granulites, but the arm has been folded up with the gneisses through which it cuts.

Of the numerous other occurrences of pyroxene-granulite, now known in various parts of the world, many have been regarded as probably igneous in origin, purely on account of their mineralogical resemblance to gabbros, norites and other known eruptives; but no direct field evidence has been discovered to prove the true nature of these peculiar rocks.

Lacroix's correlation with French gneisses.

Under the name "pyroxene-gneiss" Lacroix has described a number of specimens which were collected in the Madras Presidency as long ago as 1819 by Leschenault de la Tour. Some of these are evidently identical with members of the charnockite series. On petrological grounds alone they are correlated by Lacroix with the gneisses distinguished by the letter ζ^1 in the geological map of France, and are regarded as older than the associated hornblendic, chloritic and mica schists. At the same time the pyroxenic rocks are looked upon as members of the upper part of the gneissose series. The facts that the specimens described by Lacroix only imperfectly represent the large assemblage of pyroxenic rocks which field observations, as well as microscopic evidence, show to be genetic relatives in the Madras Presidency, and that their localities have been imperfectly recorded without field notes, detract seriously from the geological value of a memoir, which, as a contribution to our knowledge of Madras mineralogy, is highly appreciated by the Geological Survey of India. As nearly as the few data would permit I have attempted to identify the localities of the rocks described by Lacroix, and my researches in the field confirm his conclusion that the pyroxene-granulites are amongst the youngest of the foliated crystalline rocks in South India; their peculiar position

amongst the old gneisses is due, however, not to sedimentary superposition, but to intrusion and transgression after the fashion of igneous rocks.

After Ceylon, the nearest foreign relatives of our charnockite series are the few known exposures of pyroxene-granulites on the mainland of Africa and Madagascar. It will be interesting to follow up the comparison of South Indian with African and Malagasy rocks in view of the probable existence of the pre-tertiary Indo-African continent. This stretch of dry land probably had a great crystalline protaxis of which fragments are now preserved in South Africa, Madagascar, Ceylon, Peninsular India and perhaps Assam.

Pyroxene-granulites in Madagascar.

So far as we know from the specimens collected by the Rev. R. Baron, the rocks from Madagascar described by Hatch [1] as "pyroxene-granulites" very closely resemble our Indian charnockite series, and there also they are associated with pyroxenites and quartz-magnetite and quartz-actinolite schists [2] like those of South India. There is no doubt from Mr. Baron's notes that a precise comparison of Madagascar with Peninsular India would bring out some very interesting similarities in many other rocks as well as in these pyroxene-granulites.

(2) *Comparison with ancient Pyroxenic eruptives.*

In none of the numerous extra-Indian occurrences of pyroxene granulites has an undisputed origin been established by direct evidence. But in a few old crystalline areas pyroxenic formations occur which, though formerly regarded as ordinary members of the crystalline schists, are now generally considered to be eruptive, although they are too old to be given a place in the stratigraphical succession. The norites and hypérites of Scandinavia, the anorthosites of Canada, and the Cortlandt series of the United States are well known examples of such rocks.

[1] *Quart. Journ. Geol. Soc.*, Vol. XLV (1889), p. 344.

[2] See R. Baron, "Geological notes of a journey in Madagascar." *Quart. Journ. Geol. Soc.*, Vol. LI (1895), pp. 59 and 60.

Notwithstanding their greater resemblance to the foreign examples distinguished as "pyroxene-granulites" and regarded as ordinary members of the crystalline schists, it is but fair to state that mineralogically the charnockite series often show close affinities to the old pyroxenic eruptives just referred to. In the Cortlandt series, for instance, there are pyroxenites, amphibolites, hornblende, augite and biotite-norites which resemble in composition those of the complex at Pallavaram. G. H. Williams has also recorded the association of hercynite and corundum with the Cortlandt series and these minerals we know too are frequently found in connection with the charnockite series.[1]

The Cortlandt Series.

Williams[2] found similar rocks in the neighbourhood of Baltimore, Maryland, whilst in Pennsylvania, at a point intermediate between the Cortlandt series of Peekskill on the north-east and Baltimore on the south-west. Prof. J. F. Kemp described, from the supposed Archæan strip that crosses Bucks County, a mass of norite containing hypersthene, green monoclinic pyroxene, brown hornblende, garnet, magnetite and apatite. Near this rock occurs a limestone with an abundance of accessory minerals such as light-green pyroxene, titanite, rutile, orthoclase with microperthitic albite, zircon, apatite, pyrite, scapolite and plagioclase. Kemp points out the similarity existing between the minerals occurring at this point and those of the Cortlandt series at Peekskill to the north-east, and again at Baltimore and North Delaware to the south-west. He also points out that these rocks resemble many of those in the Adirondacks where the basic rocks contain titanic ores.[3]

The description of these rocks by Kemp might very well apply to some exposures of the charnockite series in the Madras Presidency, and yet, as he says, they strongly resemble also the eruptives of the Cortlandt series. Cases of this kind show how closely the pyroxene-granulites approach true eruptives in the

[1] See Williams' papers, *Amer. Journ. Sci.*, 3rd Ser., Vol. XXXI (1886), pp. 26-41 Vol. XXXI (1887), pp. 135-144, 191-199 and 243; Vol. XXXV (1888), pp. 438-448.

[2] *Bull. U. S. Geol. Surv.*, No. 28 (1886).

[3] *Trans. N. Y. Acad. Sci.*, Vol. XII (1893), p. 71.

peculiarities of composition and mineral associations which they display.

Although there is such a complete correspondence in the mineral lists it is generally not difficult to distinguish a microscopic section of a typical basic pyroxene-granulite from one of these eruptive norites. The most constant of these differences is displayed by the plagioclase-felspars: in the distinctly eruptive norites the twin-bands are sharp and clearly defined, whilst in the pyroxene-granulites the twinning is less definite and the bands show a strange tendency to thin out like wedges instead of traversing the whole crystal. Recently, Dr. Walker and I found an instance in Coorg of a mass of coarse norite, showing these well-twinned felspars, in the midst of a large area of the charnockite series (pyroxene-granulites). It was perfectly easy to distinguish a typical section of the norite from the general style of the charnockite series, but we nevertheless found it quite impossible to discover a boundary between the two formations; for the coarse-grained, massive norite became granulitic and gneissose near what should have been its boundary with the charnockites.

Anorthosites of Canada.

The differences between the typical norite of Coorg and the charnockite series around are just the differences which mark off the anorthosites of Canada from the pyroxene-granulites in the same area; but in Canada the anorthosites make up the main formation and the pyroxene-granulites are comparatively restricted in their development, whilst in Madras matters are reversed and we have but this small exposure of norite to compare with great mountain masses of the charnockite series. I have recently identified a series of anorthosites (labradorite rocks) and norites near the south border of the Raniganj coal-field. The norites are fine-grained and granulitic, sometimes foliated and sometimes showing an occasional garnet. The labradorite rocks are very variable in the size of their crystals; the ferromagnesian constituents which occur in comparatively small quantities, include an occasional olivine with well-defined reaction rims.

Norites of Scandinavia.

Whilst the American anorthosites and norites resemble the basic members of the charnockite series in their mineralogy, a much more striking analogy can be found in Norway, where Vogt [1] has described a group of hypersthenic rocks in which the basic varieties are associated with an acid form composed of potash-felspar, quartz, rhombic pyroxene and a small amount of plagioclase, thus resembling most perfectly our charnockite (*c.f.* p. 134). What makes the analogy more complete in all these cases is the similarity of the mineralogical habit, so to speak, of the chemical compound; thus we never find sphene in the unaltered members of the charnockite series, but the titanic oxide always seems to be in the form of ilmenite, and this is true also of the rocks described by Vogt. These rocks have recently been more fully described by C. F. Kolderup in the Ekersund and Soggendal areas. The types represented vary from the ultra-basic ilmenitite, through pyroxenites, norites, labradorite rocks, monzonites, banatites and adamellites to a bronzite-granite. The resemblance of these to our Madras rocks, which was indicated by Vogt's brief description of them, is brought out more strikingly by Kolderup's details, and by his direct comparison with specimens from Madras.

Reviewing the whole evidence, we must conclude that we are not yet in possession of sufficient facts to define the precise difference between these old norites and the pyroxene-granulites. Most probably they were originally similar formations, which, on account of secondary changes induced in the presumably older pyroxene-granulites, are now distinguishable by differences more easily recognised than described. However, the one important point to be considered by us at present is that between the norites which are certainly eruptive and the pyroxene-granulites whose origin is doubtful there are so many points of resemblance still left that we have good *primâ facie* reasons for expecting evidences which will show that the two groups of rocks are really similar in origin.

[1] *Zeitschr. für. prakt. Geol.*, 1893, p. 4.

CHAPTER VIII.

PETROGRAPHICAL EVIDENCE IN SOUTH INDIA.

The attempt to settle the origin of the charnockite series by correlation with its foreign equivalents leads, therefore, to results which are not conclusive. In the first place, they present certain similarities to rocks whose eruptive origin is now considered to be established, such, for instance, as the norites and related rocks of Scandinavia, the anorthosites of Canada and the norites of some parts of the United States. In the second place, they present a much more perfect resemblance to the pyroxene-granulites of Saxony, concerning the origin of which very diverse opinions have been published, whilst Lacroix has correctly indicated the resemblance they bear to the French pyroxene-gneisses.

The origin of the charnockite series must consequently be settled purely by evidence obtainable on the spot, and without regard to the results obtained for mineralogically similar foreign rocks. In dealing with a comparatively young and only slightly altered formation, one would naturally look to the local and direct evidence first as the least complicated and most straightforward order of procedure ; but with the ancient crystalline rocks, conclusions based on analogy are generally our best, sometimes unfortunately our only, evidence as to origin. The processes of metamorphism tend to reduce the points of difference between rocks of diverse origin, and the consequent tendency for them to become similar to one another is real as well as apparent. Some rocks, like the limestones and sandstones, may successfully resist any changes but those of a purely structural character, and consequently are not difficult to distinguish from rocks of igneous origin ; but others, like the shales, and especially the impure shales, may, after metamorphism, imitate igneous types too perfectly to permit safe identification ; consequently a large number

of the members of the great mass of our crystalline schists may never have their original nature satisfactorily settled. With the many theories which have been propounded to account for all the results of metamorphism, this paper does not profess to deal. The writer wishes merely to point out the evidences upon which he has based his conclusions as to the igneous origin of the charnockite series, and to indicate briefly how far the observations made are reliable data. There seems to be no reason why the knowledge we have acquired as to the properties which distinguish known igneous from unequivocal sedimentary rocks should not be applied to the old Archæan crystallines. That these very ancient rocks present peculiarities not found in any younger metamorphic rock may be true, and, on account of their great age, should be expected. That *all* their original structures have been changed beyond possible recognition may also be true locally; but it is hardly likely (and no approach to proof has been offered) that this destruction of original characters is universal. On the contrary, it is more likely that the rocks we call Archæan have undergone very different degrees of alteration in different areas (some of them thereby retaining relics of original characters), and as long as this likelihood remains undisputed, it will be more scientific to assume that the law of uniformity holds, and that we may profitably apply the experience gained from younger rocks towards the elucidation of the phenomena presented by the old crystalline gneisses and schists. At any rate, such a proceeding has greater claims upon the student of ancient crystalline regions than any single untried sweeping generalization based on a purely speculative assumption as to the origin of these rocks. A recognition of the fact that the Archæan rocks have undergone profound alterations is not necessarily inconsistent with an objection to enveloping such a large fraction of our exposures in an impenetrable mystery beyond the range of our present methods of petrographical research.

The determination of the origin of any particular formation amongst the crystalline schists depends upon (1) the physical form

and internal structures recognisable in the field, and, (2) its microscopical and chemical characters.

With younger, undisturbed, igneous masses the field relations of the rocks offer more direct and reliable evidence, whilst with the crystalline schists the field characters are more often destroyed and the question of their origin is then based on their microscopical and chemical resemblances to known igneous types: the argument is thus reduced to mere analogy. With many formations in crystalline areas the microscopical and chemical evidences are all we get or can ever expect; but with the charnockite series we have very straightforward field evidence in favour of their igneous origin, and this circumstance we have to attribute to the remarkable state of quiescence, as well as the uninterrupted and prolonged denudation, which has characterised Peninsular India for many geological ages. On this account it is less surprising to find features presented by the charnockite series which have never been noticed in the case of the pyroxene-granulites and related rocks in other parts of the world, where they have been subjected to repeated and intense dynamic metamorphism, or insufficiently uncovered by denuding agencies.

Field Characters of the Charnockite Series.

The geological features which indicate the igneous origin of the charnockite series may be conveniently classified as follows:—

(*a*) Form and structure of the great *massifs*.

(*b*) The existence of dykes and apophyses proceeding from the main mass through adjoining formations.

(*c*) Contact metamorphism of the surrounding rocks.

(*d*) Inclusions of older foreign rocks and the changes they show.

The first of these four points forms an argument based purely on analogy: we are acquainted with the usual external form and internal structures of known eruptive masses, and the presentation

of similar features by the great masses of the charnockite series in South India would be regarded as *primâ facie* evidence in favour of their igneous origin also. The last three considerations, however, are direct tests of origin and include the special phenomena through which our ideas of igneous rocks generally have been derived.

(*a*) *Form and structure of the great massifs.*

Size of the great masses.

The pyroxene-granulites of Saxony occur in the form of bands or lenses, which, compared with the great masses of the charnockite series in South India, are extremely small. The plateau of the Nilgiris covering over 700 square miles is composed almost wholly of this series. The Shevaroy hills, covering 100 square miles, represent another large mass which is extremely uniform in composition throughout, at least quite as uniform as any great igneous *massif*, say of granite or diorite, is ever found to be. Probably still larger masses occur in the Western Ghâts. There is a great difference between masses like these and the small lenses and bands of "pyroxene-granulites" of the better-known occurrences in Europe, where the small bodies more commonly vary from a few inches to a few yards in thickness. The main "granulite formation" of the Saxon Mittelgebirge is a lens some 31 miles long by 11 broad, or covering about half the area of the Nilgiris; but instead of being a similar uniform body it is a complex including, besides the different varieties of ordinary "granulite," bands of pyroxene-granulite, biotite-gneiss, cordierite-gneiss, garnet-rock, amphibolite, zobtenite and serpentine.

Shape.

These great masses of the charnockite series are either quite irregular in shape or show a roughly lenticular form. In the case of small masses the lenticular shape can often be made out very distinctly. Several small hills of the basic varieties occur around Salem and in the Salem-Ahtúr valley which show this characteristic. In one of these instances, ¾ mile E. N. E. of Karipatti in the Salem-Ahtúr valley, a river cuts

through the end of one of the lenses, giving a very clear section of the tapering edge of the lens in the highly crushed schists.

Lenticular habit.

As a general rule the rocks immediately bordering these lenses are highly crushed, often crushed beyond all possible recognition of individual minerals, whilst those which form the lenses may show merely a directional disposition of constituents parallel to the long axis of the lens, but otherwise show no signs of having been subjected to exceptional pressure; sometimes, indeed, they are quite massive. Two alternative explanations naturally suggest themselves by these phenomena: either the lenses are bands pinched out by pressure, or they are the result of intrusion between the already foliated schists. In some cases it can be shown quite distinctly that the lenses are not arranged along the same band of the schists; that in fact, they are disposed *en echelon* with their long axes parallel to one another though not in the same line. Such instances are seen to the north of Karipatti, and indicate that the first explanation is probably not applicable to all cases. The second explanation, namely, lenticular intrusions between the schists, is more generally satisfactory. Reyer would probably regard these lenticular masses as *Kuppen*, as he does in the case of the roughly lenticular granulite complex of Saxony.[1]

Homogeneity.

But whether these rocks occur as small lenses, or whether they form the larger boss-like masses, the one important point is the uniformity of average composition and character throughout, an uniformity of the kind with which we are familiar in large bosses of igneous rocks, but of which we have no parallel amongst those of sedimentary origin. Amongst sedimentary rocks our most uniform types are the marine limestones which are formed in the deep sea, where considerable changes of level are required to bring about noticeable variety in the lithological characters of the products. Under the conditions prevailing within short distances of the coastal region small

[1] Theoretische Geologie, 1888, p. 533.

oscillations of level may give us rapid alternations of shales, sandstones conglomerates, marls and carbonaceous deposits, and no amount of metamorphism short of complete fusion could ever produce uniformity of composition throughout such a complex formation of beds.

In old metamorphic rocks like the Dharwars and so-called upper division of the schists, we get beds of quartzites, hornblende-schists, mica-schists, iron-ore beds, conglomeratic schists and crystalline limestones—rocks which form comparatively narrow bands wholly distinct from one another and clearly diverse in origin and in age. There is no equivalent amongst formations like these for a homogeneous mass of rock measuring 15, 20 or 30 miles across the direction of foliation. To regard the enormous thickness of the charnockite series as the result of repeated foldings of one formation would be no help out of the difficulty, but on the contrary would leave us with the still more difficult task of finding the evidences of folding. Traverses across the foliation lines reveal no regularly repeated succession in composition and structure; for the foliation is generally a microscopic structure and the banding seldom continuous for more than a few inches (*infra*, p. 221).

Schlieren structures.

But whilst, like plutonic bosses, the masses of these rocks are uniform in their general average characters over large areas, they are seen on close examination to present precisely the heterogeneity of structure and composition which is characteristic of igneous masses—masses in which there has been sufficient freedom of molecular movement to permit local differentiation of the compounds, or segregative consolidation of the mineral constituents.

Such local departures from the average composition of the rock are spoken of by German geologists as *Schlieren*, a term which for want of an exact equivalent we might profitably borrow. Because the word *Schliere* merely indicates a structural phenomenon without regard to the ultimate cause of its origin, it is likely to convey only its structural meaning, and is therefore preferable to the equivalent expressions *segregations* and *concretions* which are used in various

senses. The fact that the word *Schliere* (or its plural *Schlieren* for which form our Anglo-Saxon plurals should prepare us) is a foreign word, will contribute to the preservation of its precise technical meaning, and I would, therefore, propose that it be used in the sense in which it is used in Germany.[1] *Schlieren* may thus be defined, as any portions of a great eruptive mass which show a definite departure, either structural or mineralogical, from the average rock, or main mass; but which nevertheless are connected with, and show their genetic relationship to, the main rock-mass by gradual passage forms. Schlieren are not sharply marked off from the rock in which they occur like inclusions of foreign rocks generally are, but, on the contrary, show under the microscope an interlocking of the constituents across the junction line. Schlieren phenomena may be due to concentration of any portion of the constituents, as in the case of the basic highly hornblendic patches so common in syenites, and the ultra-acid so-called "contemporaneous veins" in the granites; or they may be due to structural departures from the average rock, as for example the glomero-porphyritic patches in some dolerites. In other words, they may be due to variations in *composition* or variations in *structure*. These statements are quite independent of any theories as to the mode of formation of schlieren; whether they are the result of original heterogeneity of the magma, or due to subsequent segregative consolidation, is of no immediate concern to us; the important point for the present is the recognition of the features which show the genetic relationship of the schlieren to the rock in which they are found, and the distinction between them and included fragments of foreign rocks which have been picked up by accident. Both features,

[1] "Eine Schliere ist eine Partie eines Körpers, welche von der übrigen Masse differirt, mit derselben jedoch durch Uebergänge verbunden ist" (Reyer, Theoretische Geologie, p. 81). "Mit dem Namen *Schlieren* bezeichnet man die Erscheinung, dass in einer grösseren Eruptivmasse untergeordnete Partien vorkommen, welche mineralogisch oder structurell beträchtlich von der Hauptmasse abweichen, aber mit ihr durch Uebergänge verbunden sind . . Da sie keine scharfen Grenzen zeigen, sondern ganz allmählich in die Hauptmasse verlaufen, so ergeben sie sich als integrirende Theile der letzteren und dürfen somit durchaus nicht mit fremden eingeschlossenen Bruchstücken verwechselt werden; ihre Bildung hängt auch mit derjenigen der Gesteinsmasse, in welcher sie vorkommen, unmittelbar und untrennbar zusammen" (Zirkel, Petrographie, 1893, I, p. 787).

however, are points of evidence in favour of the igneous origin of the rock-mass; for the included fragment shows that the rock in which it occurs was in a molten condition, whilst the schlieren structures show that the magma must have been in a condition of free molecular movement akin to that of molten material.

When the production of schlieren results in the formation of well-defined bodies included in the normal rock (as, for instance, the dark patches so common in granites), such bodies might conveniently be named *autoliths* in contradistinction to the term *xenoliths* applied by Professor Sollas to picked-up fragments of foreign rocks (*vide infra*, p. 234). Inclusions of rock similar, and perhaps related genetically, to that in which they are included Lacroix proposes to distinguish as *homogeneous* (*enclaves homœogénes*).[1] But the peculiar meaning which we generally attach to the word *homogeneous* prevents our adoption of Lacroix's expression; the term homogeneous applied to a body would to most people (following the usage of mathematicians) imply similarity or uniformity throughout its own parts, not similarity to its neighbours, or the matrix in which it is embedded.

Basic Schlieren.

In the charnockite series a common form of schliere (autolith) appears as a dark-coloured, fine-grained, basic fragment in the ordinary grey rock, which, on microscopic examination, shows the same constituents as the main-mass, but with a smaller proportion of the white (acid) constituents, quartz and felspar. An increase in the proportion of the peculiar green-brown hornblende is an interesting feature very frequently seen in these basic schlieren, interesting because a similar increase of this hornblende always characterises the border facies of the basic types in this series, the selvages of the Coorg dykes for instance (p. 228). Like the border forms, these basic schlieren are thus products of the earlier stages of consolidation (see Nos. 11·910, 11·911, 11·917).

[1] Lacroix, "Les enclaves des roches volcaniques, 1893."

In some of the basic types, the norites, we come across lenses or bands from which all felspar has been excluded, and the rock is composed of augite, hypersthene and hornblende, with sometimes small quantities of olivine, iron-ores and green spinel (Nos. 11·891, 11·904). But in all these cases microscopic sections across the junction of the ultra-basic schliere and the less basic main-mass show no sharp line of division (specimen 9·667).

Primary eruptive breccia.

The early-formed basic material may be broken into by the residual magma and divided into angular fragments, which, cemented by the more acid subsequently intruded magma, give the rock the appearance of a breccia—the *Primärbreccia* of Sederholm and *Primärtrümer* of Lossen. Sometimes we merely meet with isolated fragments of the basic rock floating in the general main-mass; at other times the fragments of basic rock are separated by thin films of the acid variety, and at other times again an exposure may show about equal quantities of the basic fragments and more acid cement.

The late Prof. G. H. Williams proposed to use the term *protoclastic structure* for these phenomena.[1] This term has, however, been used in a slightly different sense by Brögger for describing the elæolite-syenite of South Norway, in which the mineral constituents have sometimes been crushed and broken by movement during the process of consolidation, the granulation being often accompanied by foliation and the production of eye-structure (*primäre Augenstructur*). The use of the term *primary breccia*, or more fully *primary eruptive breccia*, in imitation of Lossen and Sederholm, instead of the term protoclastic structure, will thus reduce the chances of confusion, and at the same time clearly express the nature of the phenomenon under consideration. A

[1] Fifteenth Ann. Rep., U. S. Geol. Surv., 1893-94, p. 662. "We know......that basic secretions are a common feature of slowly solidifying granitic magmas, while a partially solidified portion of such a mass may be broken into and brecciated by a subsequent intrusion of the residual magma, whose composition has slightly changed, thus producing a sort of protoclastic structure" ("Criteria for the recognition of ancient plutonic rocks in highly metamorphosed terranes", G. H. Williams).

very pretty example of this primary breccia is shown near the boat house on the shore of the Ootacamund lake in the Nilgiri hills.

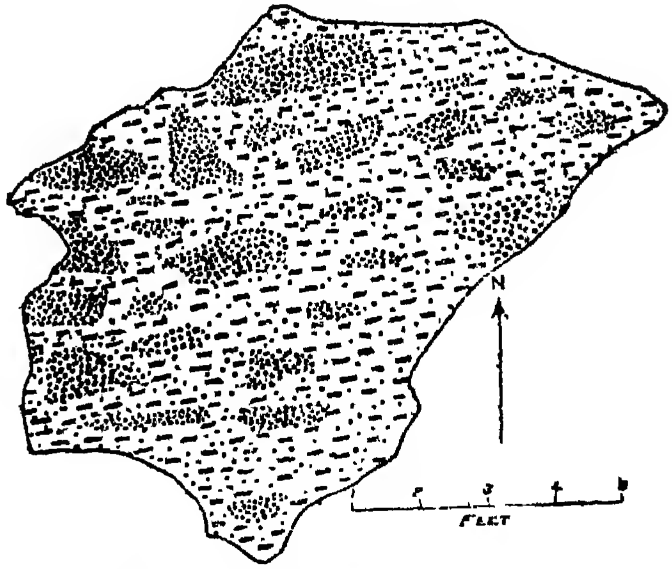

FIG. 7.—*Primary breccia: plan of exposure near the lake, Ootacamund.*

In a small exposure which has been blasted for the road cutting, some scores of angular fragments of dark-coloured, basic, fine-grained rock are seen to lie in a matrix of lighter-coloured, more quartzose and coarser charnockite. There is a fairly distinct linear disposition of the acid rock, whilst the basic fragments have their long axes also arranged, stream-fashion, parallel to the general flow (fig. 7). Although at a distance the dark fragments are plainly distinguished from the more acid matrix, close examination increases the difficulty of determining the exact line of separation of one type from the other, whilst microscopic sections show a perfectly gradual, though rapid, transition between the two. This is a constant and an essential feature in these primary eruptive breccias and is shown equally well by the junction-lines between isolated schlieren (autoliths) and the normal rock in which they lie,

Acid "contemporaneous veins."

Besides these basic autoliths, which are in general the products of an early stage in the processes of consolidation, almost every mass of the charnockite series shows instances of the acid schlieren, which generally take the form of veins, and represent, as in our

ordinary eruptives, the consolidation of the more siliceous residual portions of the magma. The old Cornish geologists described these as "contemporaneous veins" to distinguish them from "true veins" which were either distinct subsequent intrusions, dyke-fashion, or valuable mineral lodes filling fissures formed in the previously consolidated rock. These "contemporaneous" veins are the *hysterogenetic Schlieren* of Zirkel,[1] and the special form of *Schlierengänge* which Reyer distinguishes as *Secret-Gänge* or *Secret-Blätter*.[2] The essential point expressed by these terms is the genetic relationship between the acid vein and the rock it cuts, and it was this idea which led to the subsequent replacement of the expression "contemporaneous veins" by "segregation veins," a term which Boase says was introduced by Professor Sedgwick at the suggestion of Whewell.[3]

In the charnockite series these contemporaneous, or segregation veins are, in common with those well-known in plutonic masses, usually coarser in grain as well as more acid than the main rock mass which they traverse. Very clear instances are seen in the small hill on the west side of St. Thomas' Mount, Madras, where coarse-grained veins are seen cutting through the type-mass of charnockite (p. 145). The contemporaneous veins only differ from the charnockite in which they occur by this coarseness of grain and the almost complete absence of the ferro-magnesian silicate, hypersthene, which characterises the charnockite. The quartz is the same peculiar blue-grey quartz, and the felspar is the same kind of blue-grey microcline, whilst granules of iron-ore occur in both the charnockite and the slightly more acid contemporaneous veins

[1] Lehrbuch der Petrographie, 2nd Ed., 1893, p. 791.

[2] Theoretische Geologie, 1888, p. 101. The term *Blätter* so often used by Reyer instead of *Gange* expresses more precisely the form of these bodies which we habitually call "veins" because of the vein-like aspect of their outcrops on any surface. In the same way we speak of *lenses* because of the lenticular shape of the sections of bodies which are often limited by cylindrical, not spheroidal, surfaces. This additional precision is, however, of little value as long as no confusion is caused by the use of the term "vein".

[3] H. S. Boase.—"A treatise on Primary Geology," London, 1834, p. 355; Sedgwick, *Phil. Mag.*, Vol. IX, p. 284.

Professor H. Louis adopts this old view of the term "segregation" in his classification of ore deposits in the 2nd Edition of Phillips' "Treatise" (1896, p. 11, foot-note).

(Nos. 9·658 and 9·659).[1] As usual with schlieren these veins, although quite distinctly shown on weathered surfaces, are so closely united with the fine-grained charnockite that the junction line loses its sharpness in microscopic sections.

The phenomena of contemporaneous or segregation veins is not confined to the non-garnetiferous varieties. In the Nilgiris where the charnockite series are so often garnetiferous, the coarse-grained veins, composed of quartz, felspar and well schillerized hypersthenes, also include fine well crystallized garnets often as large as walnuts. A good instance is shown by a mass of rock exposed behind Oaklands, Ootacamund, and several more were revealed by blasting below Oaklands.

Schlieren phenomena are thus of two principal kinds—isolated *autoliths* which are generally more basic than the normal rock they lie in, and *contemporaneous veins* which are generally more acid than the ordinary rock they traverse.

Deformation of Schlieren and the origin of banding.

Directly connected with the schlieren phenomena, but of a special kind, is the banding so often, or rather generally, exhibited by the charnockite series. It is very seldom indeed that the bands can be traced for any considerable distance; they are, more strictly speaking, highly distorted, drawn-out lenses which give the weathered surfaces of the rocks a streaky appearance. The slight differences of composition between adjoining streaks give rise to different powers of resistance to the action of atmospheric agents, with the result that the so-called banding is always especially noticeable on weathered surfaces; indeed, it (and the foliation) is often not recognisable at all in fresh hand-specimens. As in the case of the ordinary schlieren, it is impossible under the microscope to find a sharp junction line between the dark-coloured and light-coloured bands. I believe the banding to be due merely to distortion of the imperfectly formed schlieren by flow of the magma during the process of consolidation,

[1] I have often noticed in these rocks that the highly quartzose contemporaneous veins also contain considerable quantities of iron-ore which is sometimes titaniferous. A conspicuous instance is exposed near the "Castle," Yercaud, Shevaroy Hills. It is not at all uncommon to meet with instances which show that the iron-ore is reserved for the final stages of consolidation.

and thus comparable to the banding which often characterises rhyolites in which patches of crystallites, or of coloured material, are drawn out to thin streaks by distortion of the viscous lava along one prevalent plane, the plane along which the lava flows and which is at right angles to the direction of the maximum pressure; that is, in the case of the rhyolitic lava, at right angles to the direction of gravity which produces the flow.

Whether the magma became "schlierig" by molecular differentiation *before* crystallization commenced, or whether it was the outcome of segregation *during* the processes of consolidation, is a matter of secondary concern as long as it is understood that the distortion occurred before the rock was sufficiently solid to show crush structures.[1] It is important to keep this point in mind because, whilst this kind of banding is more generally due to the mere distortion in one direction of a "schlierig" magma, there is another form of banding of a much more perfect kind, which, in some cases at least, is due to *lit-par-lit* injection (*infra*, p. 223).

This imperfect, discontinuous, lenticular kind of banding is a strong argument in itself against the idea that the banding in these rocks represents relics of an original sedimentary structure,[2] whilst

[1] Apparently, from the illustrations he employs, Reyer thinks that the "schlierig" character of a magma is developed whilst it is still in the molten condition: "Nur selten sind grössere Massen eines Körpers wirklich homogen; bei der Auflösung eines Salzes treten verschieden concentrirte Partien der Salzlösung als Schlieren nebeneinander auf, welche sich durch verschiedenen Salzgehalt, spez. Gewicht, Lichtbrechung, etc., unterscheiden. Das Meer ist schlierig; es besteht aus verschieden concentrirten und verschieden warmen Wassermassen; die Luft ist schlierig, weil sie partienweise verschieden mit Wasserdampf, Staub, etc., vermischt ist; schlecht gemischter Teig, Lava-massen, Granite sind gleichfalls schlierig; kurz wohin wir blicken, die Liquida, sowie die festen Korper sind ungleich gemischt, sie waren seit jeher schlierig" (Theoretische Geologie, p. 81).

[2] That the banding of the gneisses has any necessary connection with original sedimentation is probably held now by very few geologists; but the idea, promulgated by the genius of Lyell, naturally dies hard, and probably still influences, if unconsciously, our forms of expression. It is not rare to find, for instance, that the unconformity of the transition schists is said to be shown by their beds being found to overlap "the upturned edges of the gneiss". To those who regard the old gneisses as "portions of the primeval crust of the globe, traces of the surface that first congealed upon the molten nucleus", or who hold any such sweeping, but necessarily speculative, theory, the banding (bedding) of the gneisses may convey a concrete meaning; but it is probably more profitable to work out each gneissose formation for itself, and then to draw the simple inferences which are usually permitted for similar phenomena presented by rocks whose characters are better understood and which permit of safe deductions. There seems no adequate reason, so far, for excluding the old gneisses to the limbo of the mysterious.

the notion that it is due to mere distortion of schlieren structures by movement akin to flow, is a much simpler explanation and one which has many parallels amongst rocks whose characters are better understood.

That banding of a kind indistinguishable from that exhibited by the gneisses occurs in undoubted eruptives is shown by the striking instances occurring in the tertiary basic igneous rocks of West Scotland. On account of the resemblance of these banded rocks to some of the old gneisses and pyroxene-granulites of the adjoining areas, they were at one time considered to be portions of the old Archæan complex; but Sir A. Geikie and Mr. Teall have shown that the rocks are merely local modifications of the well known tertiary gabbros.[1] After considering two explanations, namely, differentiation *in situ* and successive intrusions, Geikie and Teall concluded that the banded structure of these gabbros is the result of the intrusion of a heterogeneous, that is, as Reyer would say, of a "schlierig," magma.

Lit-par-lit injection.

That banding may be produced, however, in some cases by successive injection is shown by the gneisses in the neighbourhood of Tirrupur, Coimbatore District. But in these rocks the banding is of a much more definite nature than that usually exhibited by the charnockite series. Although they present the essential features of the charnockite series, the rocks in the neighbourhood of Tirrupur contain an unusual amount of hornblende, and the non-felspathic forms might almost be described as hornblende-rocks. The latter occur as numerous, narrow, well-defined bands, separating the basic or intermediate felspathic forms, and giving the whole rock an extremely distinct banded structure, with a constant W.-N.-W.—E.-S.-E. strike. When the black hornblende bands, however, are carefully followed, they are found to run with the general foliation for some distance, then suddenly break across the folia and again continue their original direction, though in a different line. In a few cases the

[1] *Quart. Journ. Geol. Soc.*, Vol. L (1894), pp. 645-659.

black bands were found to bifurcate and so form two distinct bands. Both instances are shown in plate IX. Although there is no question about the fact that the hornblende rock is a distinct injection along the foliation planes of the gneiss, it never shows a chilled selvage; but on the contrary its crystals, though slightly coarser in grain than the otherwise similar hornblende of the gneiss, interlock across the junction after the manner of the schlieren already described. The hornblende bands and hornblendic gneiss which they traverse are, from the character of their constituents, clearly relatives and derived from the same magma, and the former must have been injected whilst the latter was still hot. A somewhat similar relation between the pyroxenite and norite has been observed at Pallavaram and elsewhere; but the Tirrupur case is quite the most striking instance I have seen showing that banding may be produced by successive injection of slightly different, but genetically related, rocks.

(*b*) *Apophyses and Dykes.*

Destruction of evidence.

As a general rule attempts to recognise apophyses and dykes proceeding from any large massive constituent of the crystalline schists will be attended with failure, for the very good reason that any dykes or veins originally existing will generally be squeezed out to form apparently independent parallel bands or lenticular masses without determinable connection with the main formation. The deformation of a series of radiating veins by pressure exerted in a direction at right angles to the general foliation will thus increase the resemblance to the common banding of gneisses. Moreover, there is a natural tendency for an intrusive rock to follow the cleavage and foliation planes, which is the direction of least resistance (*vide supra*, p. 223 and plate IX).

Fortunately the charnockite series appeared in South India after the close of the most severe earth-movements, and the original vein and dyke structures have not been wholly obliterated by the subsequent, feebler dynamo-metamorphism.

Transgressive tongues.

Important light is thrown on the nature of this series by a section exposed near the Namakkal road, 3½ miles south of the town of Salem. The quarry in which this section is exposed occurs at the junction of the charnockite series, which forms the great mass of the Jarugamalais lying to the east, and the old biotite-gneisses which stretch away to the west and crop up at intervals in the well cultivated plain. On the freshly exposed rock surface, tongues of the charnockite series, proceeding from the direction of the great Jaruga hill mass, are seen to protrude into the biotite-gneiss, running obliquely to the foliation planes of the latter. The charnockite forming these tongues is slightly more basic than the ordinary "intermediate" form, having a specific gravity of 2·80. The biotite-gneiss contains much quartz and is distinctly more acid in composition. In petrological characters, also, the two rocks are quite distinct: the charnockite is a compact, blue-grey, fresh-looking rock, whilst the biotite-gneiss is mottled by patches of a dark-green micaceous mineral lying in dirty-white felspar and pale-blue quartz, with, frequently, lumps of pyrite. Under the microscope the charnockite is found to be composed of hypersthene, pale blue-green augite, felspar and a little quartz with lumps of magnetite—all showing a type of rock quite common amongst the charnockite series, and displaying practically no signs whatever of dynamo-metamorphism. The biotite-gneiss, on the other hand, is not only highly crushed, but its minerals all show signs of alteration of a kind not seldom found in definite contact cases: epidote and muscovite are formed in the felspars, pyrite and rutile are fairly abundant, whilst the ferromagnesian silicates have completely lost their individuality, being replaced by an indeterminate felsitic product, patches of which are surrounded by a radiate fringe of green micaceous and hornblendic minerals, now far gone in the processes of chloritization.

If these two rock-masses, the biotite-gneiss and the charnockite, merely existed as adjacent formations, it is possible that one of them might suffer dynamo-metamorphism without noticeable alteration of

its neighbour; but when thin tongues of the two are so completely dove-tailed, it is difficult to see how the charnockite could escape the metamorphism which has been so evidently disastrous to the tongues of the gneiss. The most straightforward inference to be drawn is, it seems to me, that the charnockite attained its present position *after* the crushing of the gneiss, that, in fact, it has trespassed across the foliation planes of the latter. This implies that the charnockite has behaved after the fashion of an igneous rock, and that it is younger than this particular biotite-gneiss near Salem.

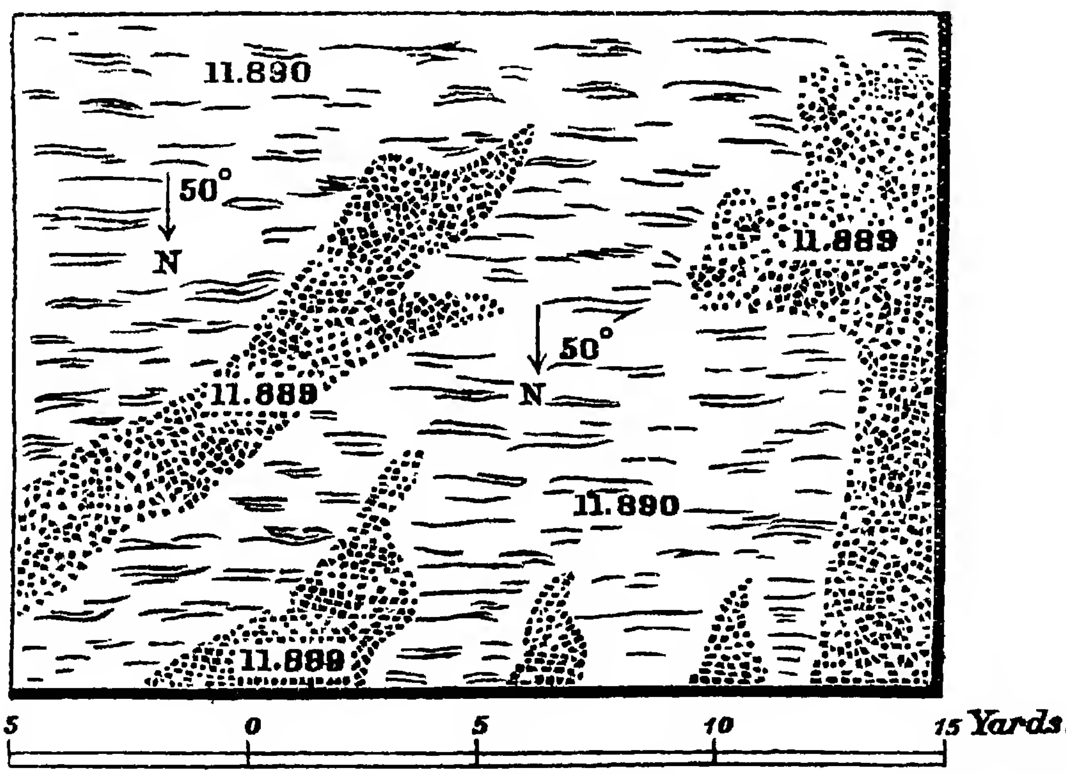

FIG. 8.—*Plan showing tongues of unaltered charnockite (11·889) corroding crushed biotite-gneiss 11·890, 3½ miles S. of Salem.*

So far the evidence is simple enough; but there are other points which must be taken into consideration:—Whilst the tongues of charnockite are easily, at a glance, distinguished from the gneiss they protrude into, close examination of the junctions show that, instead of there being a sharp line between the two rocks, there is a very rapid, though gradual, transition from one to the other. Besides this, dark patches occur in the charnockite parallel to the

dark patches of micaceous mineral which in the biotite-gneiss indicates its foliation. The charnockite veins look, therefore, as if they were pseudomorphs very imperfectly retaining the structures of the rock they have corroded and replaced. Although, therefore, there is little doubt about the charnockite having trespassed on the gneiss after its consolidation and crushing, the precise nature of this trespass is less easily defined: the interlocking of constituents at the junction-line, the absence of chilled selvages in the charnockite, the imperfect pseudomorphism of the banded structures are points which distinguish this "trespass" of the charnockite from the more usual kind of simple intrusion of one rock along fissures in an older neighbour. The tongues of charnockite, however, radiate from a large mass of the same rock and enter the gneiss without regard to the direction of the foliation planes in the latter As I can recall no other case precisely similar to the one now described, we have no previous experience to guide us to a safe interpretation of the facts; and the only explanation I can offer is that the intrusion occurred at great depths when the biotite-gneiss, being also at a high temperature, became corroded by the molten charnockite. Another explanation might be offered by those who hold ultra-metamorphic ideas, namely, local alteration and refusion of the biotite-gneiss. In view however, of the fact that the two rocks are totally different in mineralogical and chemical composition, this alternative theory seems to be unnecessary and less likely; besides, the way in which the tongues proceed from the large adjoining mass of charnockite, and the clear marks of contact action impressed on the old biotite gneiss[1] indicate that there has been a distinct trespass by the charnockite, although the action is not precisely of the kind we are

[1] A gneiss extremely like this biotite-gneiss occurs as pebbles in the Dharwar conglomerates of the Kolar gold-field. This indicates that the gneiss is older than that stage of the Dharwars. When we know more about these conglomerates it is likely that some valuable negative evidence will be obtained; for I feel very much inclined to believe that, among the rocks which we have grouped together as Archæan gneisses, there are formations very widely differing in age, and careful work should enable us to discriminate between older and younger, between sedimentary and igneous.

more accustomed to deal with when an igneous magma intrudes into a cold rock and reveals the fact by showing chilled selvages.

Dykes with chilled selvages.

The conclusions as to the igneous origin and intrusive habit of the charnockite series, based on the rather slender evidence of these trespassing protrusions in the neighbourhood of Salem, receive very material support from observations which, in company with my colleague Dr. T. L. Walker, I have recently made in the province of Coorg, on the eastern slopes of the Western Ghât range, where actual chilled selvages have been observed in dykes of rocks belonging to the charnockite series.

In the north-eastern portion of Coorg* the fundamental rocks are banded, crushed and well foliated gneisses, chiefly biotite-gneisses. Between Somwarpet and Jambur the chief rocks are, however, members of the charnockite series, forming apparently a great mass which is fringed on the south-west and on the north-east sides by bands of the same series. Although these bands are sharply defined, they run parallel to the foliation of the biotite-gneiss in which they lie, and on this account are easily distinguished at once from the younger systems of basic dykes which cut the gneisses without regard to the foliation. On account of the constant way in which these dark bands follow the foliation of the gneisses, I at first regarded them as further instances of the puzzling, but common, cases of interbanding so often observed in the old gneisses; at the same time their compact nature and jointed condition give them very much the appearance of basic trap dykes. Under the microscope they were seen to be composed of the typical constituents of the charnockite series, and were often found to be garnetiferous, and to possess a granulitic structure with the peculiar water-clear, but badly twinned, plagioclase which seems to characterise the members of this series. Subsequently, in a well exposed section of some four or five of these bands cutting through the biotite-gneiss in the bed of the Cauvery river, Dr. Walker detected the compact nature of their selvages. Microscopic examination of these selvages

showed them to be finer in grain, more basic and more hornblendic than the central portions of the bands, and similar phenomena were subsequently carefully examined and confirmed in other bands near Somwarpet on the north-eastern fringe of the main mass of the charnockite series (Nos. 12·395—12·405).

Although the selvages are not now glassy, or even felsitic, and one would hardly expect them to be so after such an enormous lapse of time, they are distinctly more compact and contain less of the white constituents than the central portions of the bands. Like the chilled selvages of ordinary dykes, too, the transition from the compact to the ordinary form is very rapid, and there is no noticeable difference between specimens taken a few inches from the selvage and those taken near the centre of a 15-foot band. The increase in the quantity of hornblende at the margins is a common characteristic of the border facies of the norite family, with which these dykes—as they must now be considered to be—are closely related in chemical and mineral composition.

Some dozens of these dykes may be counted between Somwarpet and a few miles west of Fraserpet, and four or five of them, which are sufficiently exposed, show the chilled selvages most distinctly. Those which are exposed so well in the bed of the Cauvery river at Fraserpet are found to vary considerably in thickness as they are traced in the south-east direction across the river, but no constant average diminution in either the north-west or south-east direction could be definitely determined in the short distance of about ¼ mile for which they are exposed in the river bed. One of them, which measured 2 feet 8 inches in width on the left bank, diminished rapidly near the centre of the river to less than a foot, but as quickly widened out again before the right bank was reached. Similar, but not constant, variations were noticed in the larger parallel dykes. From the size of the small one just referred to these dykes may vary up to 100 yards or more in width.

Garnets are found in most of them; sometimes concentrated in patches of indefinite outlines, at other times arranged along lines

or scattered through the rock as isolated granules. The remaining constituents of the rock are characteristic for the basic members of the charnockite series: green-brown hornblende, pale blue-green augite, hypersthene, water-clear felspar with very undecided twin bands, and iron-ores. The structure is granulitic almost invariably, but the rocks are finer in grain than the average massive form of the charnockite series; the difference in grain, however, is just the same in degree and kind as we should expect to find between, say, a large stock of gabbro and a dyke of its corresponding diabase.

Here then we have a rock which shows its intrusive, igneous origin as plainly as any diabase dyke ever does, and yet in composition and structure it shows all the essential points of the charnockite series. The instances examined are sufficiently numerous to show that we are not dealing with a merely local accident in describing what is considered to be the chilled selvages of these dykes. No one probably would be rash enough to assert that all the pyroxene-granulites we know belong to one formation, one petrographical province, but here we have rocks unquestionably igneous in origin yet similar in all essential respects to the adjacent typical pyroxene-granulites (charnockite series). With, therefore, as good ground as we usually get in petrography it is safe to accept this as a corroboration of the other evidences which point to the igneous origin and intrusive behaviour of the charnockite series.

(*c*) *Contact metamorphism.*

Imperfection of evidence.

The recognition of distinct contact zones amongst the old crystalline rocks, will, from the nature of the case, be always extremely difficult. In the first place, rocks already crystalline are seldom susceptible to the action of an invading igneous mass, and, secondly, subsequent metamorphosing agencies would obliterate the results of contact action in the oldest rocks. The difficulty of distinguishing between the results of the old contact and the subsequent metamorphism will always, of

course, make the discrimination of these phenomena amongst the crystalline schists a doubtful matter.

In the case of the charnockite series the evidence of distinct contact action is extremely limited. There is the case of alteration of the old biotite-gneiss near its contact with the charnockite tongues in the neighbourhood of Salem (p. 226). This might be considered the result of contact action if we had first established the intrusive character of the charnockite; but in itself it is insufficient proof.

Altered forms of the Mercara series.

In Coorg we have perhaps more satisfactory evidence. The Western Ghât range is composed of the charnockite series which march for some thirty miles with a group of schists and gneisses distinguished as the Mercara series. The Mercara series includes a very complex succession of highly metamorphosed rocks, many of which, judging from their composition, are almost certainly altered argillaceous sediments, whilst others, quartzites for instance, are probably altered sandstones Bands of "greenstones" are fairly common in the Mercara series and probably represent original dykes, sheets, or flows of diabase. The point of immediate importance to us, however, is the very composite nature of the Mercara series, which indicates that its constituents represent a variety of origins although they are grouped together as one formation for stratigraphical purposes. The adjoining large formation of the charnockite series, on the other hand, presents no greater variations than are usually met with in a great intrusive "stock."

The zone separating these two series of rocks has, therefore, more probably derived its "contact" features by the action of the charnockite on the Mercara series than the converse. Every continuous section across the junction of the two shows the peculiar rocks which characterise the zone of contact; and although on a small-scale map the junction would be represented by a sharp line, it is impossible to define in the field the exact point which would separate the endogenous from the exogenous phenomena. Besides the graphite, sillimanite (or kyanite) which

might have been formed by any metamorphic agency, this zone is characterised by the abundance of a peculiar purple garnet which is also found in other less doubtful cases of contact action as, for instance, when the Mercara series is altered by the great granite stock which protrudes through it in the central portions of Coorg.

Although, naturally, the testimony of these cases of apparent contact action would be insufficient in themselves to prove the igneous nature of the charnockite series, their value is accentuated by their agreement with the other evidences.

As the charnockite series never comes into contact with unaltered sedimentary rocks, but is always bordered by rocks already crystalline, contact phenomena are naturally rare; the chances of studying such instances as do actually exist are still more reduced by the frequency, almost constancy, with which the junction lines are hidden by detrital material or the thick jungle which invariably clothes the foot regions of the charnockite hill-masses in South India.

Scapolitic granulites and calciphyres.

The frequent association of the charnockite series with scapolitic rocks and with the crystalline limestones, cipolins and calciphyres containing an abundance of accessory minerals, would naturally call for a place in this discussion of contact phenomena; but the field evidence bearing on the relation of these rocks to the charnockite series is altogether too imperfect to settle the question as to whether the crystalline limestones have developed their accessory minerals as part of the metamorphism of ancient sedimentary limestones, or whether they are the extreme results of alteration in the pyroxenic rocks themselves.

That this association is accidental is in the highest degree improbable, for the scapolitic rocks, cipolins and calciphyres are found associated with the pyroxene-granulites in many parts of the world.[1] One's first impulse is to regard the accessory minerals in the limestones as exogenous contact phenomena and the scapolites, anorthites, lime-augites and sphenes in their pyroxenic neigh-

[1] *Cf.* Lacroix, *Rec. Geol. Surv. Ind.*, Vol. XXIV, pp. 157 and 199.

bours as the results of endogenous contact action, due to the absorption of lime from the calcareous rocks which have become invaded; but the field observations are of too fragmentary a nature so far, to permit safe criticism of this point. And unfortunately for this apparently simple conclusion the elaborate study by Professor Judd of the similar rocks in Burma has led to results which rather indicate that the calciphyres are the results of extreme alteration of the pyroxenic rocks, the formation of the scapolite being merely a stage in the process. Professor Judd is, at the same time, inclined to consider the pyroxene-granulites, which are associated with, and possibly in part changed to, the scapolitic and crystalline limestones, to be of igneous origin.[1]

Although, therefore, the results obtained by Professor Judd necessitate the exclusion of these scapolitic rocks and crystalline limestones from the category of contact products until the field relations for each particular occurrence have been studied in detail, they are not antagonistic to the arguments here advanced in favour of the igneous origin of charnockite series.

The phenomena which we can safely regard as unequivocal contact effects caused by intrusion of the charnockite series are thus very meagre; but it is very interesting to notice that few as they are they are remarkably similar to contact phenomena produced by the intrusion of pyroxenic rocks whose igneous nature is now disputed by no one.

In the case of the Cortlandt series, for example, the late G. H. Williams has traced out the action of the norites and related diorites on the associated crystalline schists. The intrusive rocks grouped together in this area cover some 25 square miles, and are surrounded by different crystalline rocks—gneiss on the north, limestone on the west and mica schist to the south. The gneisses are not noticeably affected at the contact; but the mica schists and limestones are strikingly altered. The contact phenomena are of an endogenous (inverse) as well as of an exogenous (everse) kind. In the case of the

[1] "The Rubies of Burma and associated minerals," *Phil. Trans.*, Vol. 187 (1896), p. 151.

mica schist the quartzose lenses with garnet and other contact minerals, staurolite, kyanite and sillimanite, are developed as the intrusive rock is approached. At the immediate contact, the rocks become felspathic and their structure changes to a harder, more massive form. The eruptive rocks take on alumina and lime with simultaneous loss of silica and alkalies to the schists, and develope garnets, scapolite and other reaction minerals. The limestones become bleached and develope hornblende and pyroxene, whilst the invading rocks become simultaneously more calcareous, and the rhombic ferromagnesian pyroxene, hypersthene, is replaced by the monoclinic lime-bearing diallage.[1]

(*d*) *Included fragments of foreign rocks.*

The tendency for fragments of foreign rocks to lose their individuality by contact metamorphism when immersed in a plutonic mass becomes accentuated when the latter suffers subsequent metamorphism itself. In all attempts to prove the igneous nature of any formation amongst the crystalline schists it is consequently only natural to expect that evidence on this score will be comparatively difficult to obtain. But there are cases of bodies included in the charnockite series which I should consider to belong to this category, and the ellipsoidal masses of corundum-bearing rock found within, but near, the border of the charnockite series in the Salem District are probably examples.[2]

[1] Williams' papers on the Cortlandt series, appeared in the *Amer. Journ. Sci.*, Vol. XXXI (1886), pp. 26—41; Vol. XXXIII (1887), pp. 135—144 and 191—199; XXXV (1888), 438—448. The references made to them here are not intended to imply that the charnockite series are strictly comparable to the Cortlandt series; but the comparison of phenomena presented by known eruptives should guide us to an interpretation of those which characterise mineralogically similar rocks whose origin is under investigation. In many points the mineralogy of the charnockite series presents close analogies to that of the rocks which have been worked out so exhaustively by Williams in the Cortlandt area.

[2] These corundum-bearing bodies have been described by Mr. Middlemiss as lenticles, but the word ellipsoid is more accurate and indicates an essential difference in meaning. Lenses are eye-shaped in section; that is, they have pointed ends, and inclusions of this shape, which are so common in the gneisses, are regarded as drawn-out schlieren or pinched-out bands; but the rounded ends of these corundum-bearing inclusions and the peripheral concentration of biotite indicate corrosion and reaction with the surrounding rocks.

Similar bodies, with fine ruby-red corundum, have recently been found near the margin of the Bargur charnockite mass at Badavadi in the Mysore State (11°50; 77°6').

Xenoliths and schlieren (autoliths).

A distinction must of course be drawn between inclusions of older foreign rocks which bear no family resemblance to the rocks by which they have been picked up, and the schlieren (generally basic) which are formed by segregative processes during the consolidation of the rock, and which always present some signs of relationship to the rock in which they appear to be included. It is with the former bodies, *xenoliths*, as Sollas[1] aptly calls them, that we have to deal with now; the others are discussed on another page (217).

Corundiferous xenoliths.

These corundiferous bodies were originally described by Middlemiss as local modifications of the "biotite gneiss" in which they are included.[2] Subsequently the same author mentioned the hypersthene which occurs with the biotite in this gneiss, and then so far modified his previous nomenclature as to regard the rock as a passage form between the ordinary charnockite series and the Hosur biotite-gneiss.[3] In another section of this memoir I have given my reasons for concluding that the rock in which these corundiferous bodies occur is in no genetic sense related to the Hosur biotite-gneiss, but is a normal member of the charnockite series, the prevalent form belonging to the "intermediate" type.

The ellipsoidal bodies are not, in my opinion, the results of mere re-arrangement and alteration of the minerals composing the rock in which they occur, but on the contrary are composed of totally distinct minerals, possess an altogether foreign structure

[1] *Trans. Roy. Ir. Acad.*, Vol. XXX (1894), p. 493. Inclusions of rocks similar, and perhaps related genetically to the rock in which they are included, Lacroix proposes to distinguish as *homogeneous* (*Enclaves homœogenes*); but the peculiar meaning we generally attach to *homogeneous* prevents our adoption of Lacroix's expression. The word *autolith*, in contradistinction to *xenolith* would have been a better term than *homogeneous inclusion*.

[2] *Rec. Geol. Sur. Ind.*, Vol. XXIX (1896), p. 44.

[3] *Ibid.*, Vol. XXX (1897), p. 119.

and are almost certainly altered inclusions of some foreign rock. The most abundant constituent of these inclusions is a microperthitic or cryptoperthitic felspar with which is associated a series of typical "contact" minerals—corundum, sillimanite, rutile and green spinel (pleonaste or hercynite). At the periphery of each of these inclusions there is generally a concentration of biotite, flakes of which exist in smaller quantities also in the charnockite around. The corundum forms larger crystals than any of the other constituents of these xenoliths; they have an elongated barrel-shape, about three times as long as they are broad, and vary in size from crystals 6 or 7 inches long down to microscopic granules. Each large corundum crystal is surrounded by a distinct crystallization "court" of granular felspar, slightly coarser in grain than the rest of the matrix, and practically free of the other accessory minerals. The felspars of the xenoliths are perfectly granulitic in structure, the granules being crossed by streams of sillimanite needles, which, as usual, disregard the crystal-boundaries of their host and strike across the boundary lines from one granule to another. The charnockites in which these inclusions occur are well foliated, and the long axes of the ellipsoids are arranged approximately parallel to the foliation. The concentration of biotite around the periphery of each corundiferous xenolith is probably the result of reaction between the charnockite and the foreign rock.

I can recall no cases exactly parallel to these remarkable corundiferous xenoliths. Corundum, sillimanite, green spinel and rutile have frequently been found in foreign fragments enclosed in volcanic rocks, and in most cases they are regarded with good reason as the results of contact-metamorphism.[1] But it is of course inadmissible to compare the metamorphism of inclusions in a volcanic rock with the effects produced on fragments caught up in plu-

[1] See Lacroix: "Les enclaves des roches volcaniques," 1893; and Lagorio: "Pyrogene Korund, dessen Verbreitung und Herkunft." *Zeitschr. fur. Kryst*, Vol. XXIV (1895), pp. 285—299.

tonic masses. For the time, therefore, these corundiferous bodies must be looked upon as doubtfully, though for theoretical reasons, probably, foreign material enclosed in and metamorphosed by the charnockites. Their position near the margin of the large charnockite masses also favours this conclusion. Unfortunately this boundary line between the charnockite series and the adjoining biotite-gneisses was not traced out during the course of the survey by Mr. Middlemiss. Besides these examples found near Palakod (12° 18′; 78° 8′) in the Salem District, similar instances, with beautiful ruby-coloured corundum, have recently been found by Captain Campbell, R.A., at Badavadi (11° 50′; 77° 6′) in the Mysore State, where the xenoliths occur near the margin of the charnockite mass forming the Bargur hills. A fairly close parallel to the phenomena observed in these corundiferous xenoliths occurs in connection with the well known Klausen norites and enstatite diorites described by Teller and von John. These authors have described foreign inclusions in the Klausen rocks composed of andalusite, corundum, biotite, garnet and apparently orthoclase.

Chemical and Microscopical Evidence.

To the petrographer the chemical composition and the microscopical characters of rocks are criteria which rank with the larger features recognisable in the field for importance and reliability. In an area where the deformation of rocks has been carried to a high degree, these features are often the only ones left which give any unequivocal indication of origin. The chemical is more valuable than the microscopical method; for a rock may be so profoundly deformed that all the minute structures have been destroyed and even new minerals formed by internal re-arrangement of the chemical compounds, but the bulk analysis of the rock might still be not far removed from that of the original material. In the following pages these two features are treated in order.

CHEMICAL COMPOSITION.

In view of the fact—(1) that there are certain general differences between sedimentary and igneous rocks in composition, and (2) that the bulk analysis of rocks are only altered to a limited degree by metamorphism, chemical analysis of a gneiss, or of any rock metamorphosed by physical processes, should afford a clue to its origin.

By the application of these principles to a number of analyses of gneisses, Rosenbusch found that whilst some agree with known igneous types, other gneisses show no chemical similarity to rocks of igneous origin. He concluded, therefore, that the first class of gneisses, which he calls *orthogneisses*, are merely deformed igneous masses, whilst the other types (*paragneisses*) are composed of altered sediments.[1]

The most general chemical differences between igneous rocks and mechanically formed sediments are due to the removal in solution of the alkalies and alkaline earths during the decomposition of the former. This process is, of course, only partially accomplished when, as is more often the case in cold climates, disintegration exceeds decomposition; so that a metamorphosed arkose may chemically differ but slightly from a foliated granite. Gneisses so formed would, however, be limited in distribution and thickness, and the chemical evidence thus increases in value with the size of the formation.

The few chemical analyses which have been made show that the types included in the charnockite series contain the alkaline bases like their mineralogical equivalents amongst ordinary igneous rocks. In the type mass of charnockites at St. Thomas' Mount which contains much microcline, potash exceeds the soda, whilst in the intermediate and basic types the latter alkali is in excess. In other respects also the four types of the charnockite series present a general chemical likeness to many published analyses of granites, diorites, norites and pyroxenites respectively.

[1] "Zur Aufassung der chemischen Natur des Grundgebirges." Tschermak's min. und petr. Mitth., Vol. XII (1891), p. 49.

MICROSCOPICAL CHARACTERS.

As with the chemical composition, so also with the microscopic structures : certain general characters distinguish rocks of igneous from rocks of sedimentary origin, and they are often only partially masked by the results of metamorphism. Though the deformation of igneous masses may result in the complete destruction of the microscopic characters, traces of the old structures can often be detected with the microscope. Such characteristic igneous structures as basic schlieren, contemporaneous veins and primary breccia have already been described in the charnockite series, and it is only locally that they are deformed sufficiently to permit the destruction of these features.

In extreme cases of metamorphism, the development of new minerals by molecular re-arrangement of the chemical compounds may result in the formation of a rock mineralogically distinct from the original material, but still the alteration products of an igneous would present certain contrasts to those of a sedimentary rock. Hornblende, almandine garnet, epidote, sphene, and muscovite are examples of common secondary minerals manufactured by alteration of igneous rocks, whilst the metamorphism of calcareous sediments produces wollastonite and colophonite, and of clays or other aluminous materials, kyanite, sillimanite, hercynite, corundum and rutile are characteristic products.

A review of the charnockite series with these points in mind discovers no features which indicate a sedimentary origin, but nevertheless brings out the fact that they differ from normal igneous rocks in two important structural details—(1) igneous masses of any great size generally show at some point or other a porphyritic phase; and (2) generally exhibit a more or less definite order of succession amongst the constituent minerals. These two points are interdependent and may be considered together.

Even-grained structure and oscillations in order of crystallization.

A well defined porphyritic structure has been observed in the charnockite series in one case only, the porphyritic crystals being orthoclase set in a matrix

resembling the ordinary charnockites (No. 13·177). Lacroix[1] has referred to the oscillations in the order of succession which characterise these pyroxenic gneisses and which distinguish them from normal igneous rocks. Exactly why there should be this difference between simple eruptives and the old crystalline rocks has not been fully explained; but in this case, as in the case of the elæolite-syenite of Sivamalai,[2] the general absence of idiomorphism and the apparent contradictions in the order of crystallization may in some cases be explained by movement of the magma during the process of consolidation, just as, according to Professor Judd, the ophitic frameworks of augite around plagioclase break up to form a granulitic aggregate when dolerites and basalts are disturbed by movement during the process of crystallization.[3] In many of these very ancient rocks a panidiomorphic structure has been produced by recrystallization of the minerals. Stages of the process are often observed in the old dyke-rocks of South India.

Becker[4] has suggested that the production of the porphyritic structure of some lavas and dyke-rocks is favoured by the freedom of molecular translation arising from a high degree of fluidity, whilst the even-grained texture of massive rocks is due to consolidation of a less perfectly molten magma in which molecular movement is comparatively restricted. For this reason Becker thinks that the porphyritic crystals are formed when the magma is very mobile, whilst the granular groundmass of the same rocks is formed when, by reduction of temperature, the viscosity of the magma becomes increased. The extension of this interesting speculation to the charnockite series would form a partial explanation both of the absence of porphyritic structure and of the limited degree of differentiation which has taken place in the great masses.

But the banding and foliation, without crush structures, amongst

[1] *Rec. Geol. Surv. Ind.*, Vol. XXIV, p. 162.
[2] To be described in *Mem. Geol. Surv. Ind.*, Vol. XXX, part 3.
[3] *Quart. Journ Geol. Soc.*, Vol. XLII (1886), pp. 68, 76, and plate V.
[4] *Amer. Journ. Sci.*, Vol. XXXIII (1887), p. 50.

other features which characterise so many of the charnockite masses, show that deformation has occurred whilst the magma was still in a plastic condition, and one accompaniment of such deformation would in all probability be the production of a granulitic structure in which groups of granules would represent the break-up of larger individuals of the same species. If this be accepted, we have a simple explanation for, not only the granulitic structure, but also for the constant tendency there always appears to be for the minerals to present themselves in groups of like kind. This feature has been noticed in many of these ancient, foliated igneous rocks, in the elæolite-syenite for instance of Coimbatore.

Phenomena resulting from the crushing of a solid rock and structures resulting from deformation during the process of consolidation are not, however, distinguishable from one another with sufficient certainty to permit dogmatic conclusions on this score. It is difficult, if not impossible, to distinguish between the granulation of constituents already formed and the formation of crystals from many centres due to disturbance of the molecules during crystallization. Probably in all cases of movement during the process of consolidation, the ultimate phenomena are the combined result of these two processes acting simultaneously.

CHAPTER IX.

SUMMARY.

It is proposed to employ locally the term *charnockite series* for a group of hypersthene-bearing rocks which form the largest single section of the Archæan gneisses in Peninsular India. The nearest foreign equivalents of the types included in this group are found amongst the rocks known to German petrographers as "pyroxene-granulites" and to the French as "pyroxene-gneisses;" but in many points members of the charnockite series present analogies also to the "hyperites" and "norites" of Scandinavia, as well as to the "anorthosites" of America. In consequence of these facts, and with a view to facilitate the description and mapping of our Archæan sub-divisions, a distinct name with a purely local application is given, and this is not intended at present for use outside India.

The members of the charnockite series are considered to be igneous in origin, and to present intrusive relations to the associated older schists and gneisses. Although the evidences on this score, as might be expected with any very ancient eruptive, have been partially obliterated and masked, the remarkably long geological quiescence experienced by South India has afforded rare and unusual chances for the preservation of the original features in our Archæan gneisses. With so many significant characters in perfect accord it is difficult to avoid the conclusion that the phenomena presented by the charnockite series are really original features due to an igneous origin and an intrusive habit, not merely fortuitous or produced by subsequent metamorphism.

The following features—for which we have no reasons to regard as other than original—indicate an igneous origin for these rocks:—

(1) Large uniform masses of the charnockite series, either quite irregular in shape, or showing a roughly lenticular form, stand up in the midst of the more complex groups of gneisses and schists, forming mountain masses like the Nilgiris, the Palnis, the Shevaroys and smaller hills in the

Madras Presidency. Alhough the Nilgiri mass, for instance, covers an area of some 700 square miles with an average elevation of over 7,000 feet, it is composed almost wholly of the charnockite series, which retain their characteristic features throughout and are sharply marked off from the gneisses and schists of the surrounding plains below. No such thickness could be paralleled by a homogeneous formation of any sedimentary rock.

(2) Internally the large charnockite masses show the characteristic structural variations of common igneous massifs—basic, fine-grained, segregative schlieren (*autoliths*), coarse-grained, acid, contemporaneous veins, and primary eruptive breccia—features indicative of the free internal molecular translations which are presumably characteristic of, and restricted to, rocks which have passed through a molten condition. The frequent directional arrangement of the constituents presents no feature at variance with the similar phenomenon seen in igneous masses, and the imperfect banding is no more than would follow the deformation of an imperfectly segregated (schlierig) magma.

(3) Apophyses have been observed protruding from a large mass into crushed, altered and older biotite-gneiss, whilst well-defined dykes—often garnetiferous—have been found with fine-grained, basic selvages, due presumably to chilling at their contacts with the older gneisses.

(4) Although the charnockite series are too old to be found in contact with any but rocks already crystalline, fairly well-defined contact phenomena have been recognised near their junctions with quartzites, and, less certainly, in the neighbourhood of limestones.

(5) Ellipsoidal bodies composed principally of pink microperthite, with corundum, sillimanite, rutile, hercynite and biotite, possessing characters strange to the normal

charnockite series, and apparently of foreign origin, have been found included in these rocks, and are regarded as xenoliths picked up and altered by the charnockites.

(6) In chemical composition the ordinary members of this series have their nearest equivalents amongst known igneous rocks, and from the chemical evidence they would be classified with Rosenbusch's *orthogneisses*.

(7) Mineralogically the basic and ultra-basic types are precisely similar to the igneous norites and pyroxenites; the acid and the common intermediate types correspond in general to enstatite-granites and pyroxene-diorites respectively, though these, especially the former, are too rare to permit general comparisons.

The evidences by which the origin of a rock mass is determined naturally suffer partial obliteration by subsequent geological changes, and in consequence of their great age some of the phenomena referred to above are not as simple and straightforward as would be expected if these rocks had invaded younger sedimentary formations. Although, however, each point of evidence would alone be insufficient to prove the igneous origin of the charnockite series, the consistent agreement of all the ordinarily recognised tests—direct and by analogy—is far too striking to be overlooked. No evidence, moreover, has been discovered which is definitely inconsistent with our conclusions as to the origin of these rocks, though there are some features which are sufficiently unusual in normal igneous rocks to demand a special explanation. For instance,—

(1) The persistent granulitic structure and the almost constant absence of pronounced porphyritic crystals is remarkable for such large masses of igneous rocks. Similar features have, however, been noticed as persistent characters of the gneissose elæolite-syenites of Coimbatore, the anorthosites of Bengal and the norites of Coorg—rocks whose igneous origin it would be ridiculous to question. Stages

in the change from an ophitic to a granulitic structure can be traced very clearly in many of our ancient diabase dykes: it is a secondary change in which the dirty lath-shaped felspar crystals become transformed into water-clear granules, and to such a process the granulitic structure of many old igneous rocks may be due. In some instances, however, granulation may be the result of movement towards the close of the consolidation processes. Although the granulitic (panidiomorphic) structure is so very general, Mr. Middlemiss has called my attention to a well marked porphyritic phase in the charnockite series near Chennimalai, Coimbatore District.[1]

(2) To account for the frequent presence of garnets, sufficient evidence has been obtained to indicate their formation at the expense of the pyroxenic constituents. Assuming that pyroxene is stable at high temperatures and hornblende the stable form of the same compound at lower temperatures, Adams concluded that the persistence of pyroxene in the highly crushed portions of the Canadian anorthosites indicates the action of dynamo-metamorphism at high temperatures. Whilst adopting such an explanation for the preservation of pyroxene in the charnockite series, I would suggest that by continued exposure to some intermediate temperature, a change occurs in the complex ferromagnesian silicate, with molecular segregation into a more basic compound, which crystallizes as garnet, and a more acid compound, which simultaneously forms quartz or an acid plagioclase felspar, and which forms isolated inclusions in, or a graphic intergrowth with, the garnet.

(3) The linear disposition of the constituents, as well as the alternation of mineralogically dissimilar bands, have been so frequently observed in unequivocal intrusive rocks that

[1] No. 13·177. The rock has a specific gravity of 2·74, and contains the ordinary constituents of charnockite with porphyritic orthoclase crystals measuring $\frac{1}{2}$ to $\frac{3}{4}$ inch across.

such phenomena can hardly now be referred to as inconsistent with an igneous origin. The "foliation" of the charnockite series is, however, much less pronounced as a rule than that of the accompanying gneisses and schists, and is sometimes practically absent, especially in the central portions of large masses, whilst the "banding" is generally a mere streakiness of aspect due to a definite directional deformation of a schlierig mass, and not due, as in the schists, to continuous bands of dissimilar mineral aggregates.

The charnockite series being so widely distributed and abundant in the southern parts of the Madras Presidency, their study in the field naturally brings one into frequent contact with the associated gneisses and schists. The writer's observations agree with the conclusions of previous workers as to a general division of these rocks into two main types:—

(1) A fairly homogeneous, generally granitoid, gneiss—the *fundamental* or *Bellary type*[1] of gneiss—apparently occupying a stratigraphically inferior position, and, with less satisfactory reasons, considered older than,

(2) A composite group of schists and gneisses made up partly of material resembling deformed igneous rocks (orthogneisses of Rosenbusch) and partly of schists which in composition suggest the metamorphism of sediments (paragneisses of Rosenbusch). These have been referred to as the *upper* or *Salem type*.[1]

Mr. Foote has distinguished a system of less perfectly crystalline schists under the name *Dharwar System*. These rocks form a series of long bands of highly disturbed beds, folded and faulted into the gneisses, with a general N.N W.—S.S E. trend, and exposed in the highlands of Mysore and adjacent parts of the Madras Presidency.

[1] These two terms—"Bellary type" and "Salem type" of gneisses and schists—were brought into use by Mr. R. Bruce Foote, and correspond respectively to the divisions "Bundelkhand" and "Bengal" used by Mr. Foote's predecessors and contemporaries in the northern parts of the Peninsular protaxis.

The following points of revision suggested by recent work are purely local in their effects:—(1) The *magnetic iron-ore* beds and associated hornblendic gneisses in the southern parts of Madras are probably altered representatives of the hematitic quartzites and chloritic or hornblendic schists of the Dharwar system. (2) Certain exposures in South India hitherto grouped with the gneisses are now separated and regarded as later intrusives, old enough, nevertheless, to be themselves foliated in the same general directions. They are—

(*a*) the charnockite series,

(*b*) the elæolite-syenites and augite-syenites of Coimbatore,

(*c*) the porphyritic augite-syenites and ægirine-granites of Salem,

(*d*) the central granite and the norite masses of Coorg.

In addition to the above, the old rocks of South India are traversed by intrusive rocks sufficiently young to have escaped sensible deformation, namely,

(*e*) the mica-bearing pegmatites of Nellore,

(*f*) the Sankaridrug and Namakal granite,

(*g*) the older diabase dyke rocks generally following the foliation lines and often slightly amphibolized.

Still later than these there are intrusives quite independent of the foliation directions, and altogether undisturbed by mechanical movements, namely,

(*h*) peridotite masses, quartz bosses and quartz-barytes veins,

(*i*) olivine-norite, augite-norite and diabase (augite-diorite) dykes of presumably Cuddapah (older palæozoic) age,

(*j*) olivine-norites and diabases of presumably Deccan Trap age.

There is direct evidence in favour of regarding the charnockite series as younger than the two divisions of the gneisses and of the schists which are considered to be the altered equivalents of *some* of the Dharwars. There is also proof that the charnockite series is older than the groups *h*, *i* and *j*, and probably older than

e, *f* and *g*. But no facts have so far been obtained to show its relations to the other foliated eruptives, *b*, *c* and *d*. The writer agrees with the older workers in regarding the charnockite series as part of the Archæan complex, and in placing them in the upper division of these rocks; but he considers that their position has been obtained by intrusive trespass, like that of the anorthosites of America and like that of the hyperites and norites of Scandinavia.

Study of the charnockite series has brought the writer into frequent contact with the peculiar stucture referred to by previous workers in South India as "trap-shotten". The so-called "trap-shotten" bands coincide with lines of dislocation, and the black tongues and films which superficially resemble compact "trap" have the microscopical characters of mylonite which has been hardened—fritted and rarely half-fused—by the heat generated through the dislocation being confined to narrow bands, and thereby causing a higher local rise of temperature than would result from a general deformation of the rock-mass.

The phenomena of schlieren (p. 215) are frequently displayed by the charnockite series. Sometimes acid, coarse-grained contemporaneous veins (p. 219) are found cutting through intermediate and basic masses; sometimes basic segregations are cemented in an acid matrix to produce a kind of primary eruptive breccia (p. 218) or merely occur as isolated bodies in a more acid matrix. Such included bodies differing in composition from the general rock masses, but nevertheless derived from the same magma and thus genetically related to the latter, the writer would, for the reasons given on p. 217, distinguish under the name *autoliths*, in contradistinction to the term *xenoliths* suggested by Professor Sollas for inclusions of a foreign rock. In most rock-masses such autoliths will be more basic than the matrix in which they are included, but they are not necessarily so.

As is the case with all large magma bodies, the contacts of the charnockite series with adjacent crystalline formations take the

form of more or less wide reaction zones, in which the peculiarities of the charnockite series on the one hand and of its neighbour on the other are found to be intermingled. But it is not difficult, nevertheless, to distinguish between such apparent passage forms, which separate dissimilar igneous types, from real transitions, which join genetically related, adjacent, igneous masses. Marginal interpenetrations and wide zones of contact products may increase the difficulties of delineating the boundaries of large crystalline masses on large-scale maps, but such border difficulties do not detract from the individuality of the main-mass as a geological unit. Near the junction, for instance, between the charnockite series and the great gneissose granite of the Baramahal division of Salem, there might be local difficulties in drawing a sharp boundary line, but, by all the points which constitute rock individuality, the contrasts between these two formations are unmistakeably marked.

The average composition, and by far the most prevalent type, of the charnockite series has an intermediate silica percentage (see p. 146), and the occurrences of anything approaching large masses of acid or basic types are comparatively rare, whilst pyroxenites never form more than narrow bands or small lenses. Although these four distinct types belong to separate rock groups, if regarded from the purely lithological point of view, there is no doubt about their consanguinity; and the writer would consequently refer to the charnockite series as another instance which shows that, from a geological survey standpoint, the recognition of petrographical provinces is a much more natural system of classification than the customary subdivision of rocks according to silica percentage, which is true only for hand-specimens and of value only in the laboratory, but possibly still a convenient system for imparting lithological information to elementary students.

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G. I. C. . O.—No. 16 D. G. Survy.—1-8-1900.—380.

Plate VII.

Microscopic characters of the four chief types.

Fig. 1 represents the acid type or charnockite proper, which is composed of colourless quartz and microcline with a small amount of hypersthene and opaque black iron-ores. Specimen No. 9,658.

Fig. 2 shows the common variety of "intermediate" composition from the Shevaroy Hills. Hornblende and augite generally accompany the hypersthene.

Fig. 3 represents the typical basic variety from near St. Thomas' Mount (No. 9,657), which is composed of water-clear, basic plagioclase, hypersthene, augite, opaque, black iron-ores and smaller quantities of hornblende and apatite.

Fig. 4 shows a section of pyroxenite which is composed essentially of hypersthene and augite, generally with hornblende, hercynite and, rarely, olivine (No. 9,672).

All the sections have been drawn under low powers magnifying about 15—20 diameters.

GEOLOGICAL SURVEY OF INDIA.

Holland, Charnockite Series

Memoirs Vol. XXVIII Pt. 2 Pl. VII.

Fig 1

ACID

Fig 2

INTERMEDIATE

Fig 3

BASIC,

Fig 4

ULTRA-BASIC

LEADING TYPES OF THE CHARNOCKITE SERIES.

Reg No 261, Dte, Geol. Sur.—June 99—590.

Litho, S.I.O., Calcutta.

Plate VIII.

Microperthitic structures.

Figures 1, 2 and 3 show three forms of microperthitic structure frequently displayed by the charnockite series. In fig. 1 large, irregular, vermiform inclusions of a striped felspar occur in addition to the finer spindles. In fig. 2 the groundmass is microcline and the microperthitic inclusions are of a felspar having lamellar twinning. In fig. 3 untwinned felspar includes two sets of twinned inclusions.

Fig. 1 is a photograph of	section No.	1442 × 35	diameters.
„ 2 „ „	„ „	1428 × 60	„
„ 3 „ „	„ „	1876 × 20	„

All photographed with Nicols crossed.

Secondary alterations.

Figure 4 shows the schiller plates in a crystal of hypersthene from coarse charnockite (No. 8,761) obtained near Coonoor, Nilgiri Hills. Section No. 1754 magnified by 20 diameters.

Figure 5 shows the alteration of felspars in a member of the charnockite series which has been invaded by peridotite intrusions in the "Chalk Hills" near Salem. The felspars, except in the immediate precincts of hypersthene crystals, are crowded with minute black inclusions which can be individualized only with a $\frac{1}{10}$ inch objective. The inclusions are arranged in rows parallel to the twin planes of the felspar. Specimen No. 9,689; section No. 1791 magnified by 35 diameters.

Figure 6 shows a spongy garnet corona around hypersthene, with the quartzose by-product forming an intermediate layer between the two minerals (see p. 161). Specimen No. 11,903, Nagaramalai, near Salem. Section magnified by 80 diameters.

Fig 1

Fig 2.

Fig 3.

Fig 4.

Fig 5.

Fig 6.

STRUCTURES OF CHARNOCKITE SERIES.

Photographed by T. H. Holland

Photogravure

Survey of India Offices, Calcutta, October 1898

Plate IX.

Banding by injection along the foliation planes.

Near Tiruppur in the Coimbatore district the outcrops of the charnockite series are extremely well banded by alternation of felspathic and non-felspathic types. The bands of the latter are sometimes seen to break across the foliation planes and sometimes to bifurcate; they are thus, in all probability, later injections into the felspathic rock, and, though generally following the foliation planes, have betrayed their real nature by occasional departures from this rule. Banding caused by such *lit-par-lit* injections is of a much more definite kind than that caused by the deformation of schlieren (see pp. 183 and 223).

Plate X.

Concentric weathering with formation of kankar in an ultra-basic band.

The ultra-basic bands which have been injected along the foliation planes (see plate IX) often show concentric weathering like basic dykes. In the Coimbatore district, where the climate is moist during the monsoon without great precipitation of rain, the rocks are decomposed, and, on account of the limited circulation of subaërial water, the lime is only partially carried away from the decomposition products. Instead therefore of obtaining a ferruginous product like the laterite which is formed on the Western Ghâts, where the rainfall is heavy, a calcareous and argillaceous kankar is formed by weathering.

Plate XI.

Lens of Garnetiferous Norite near Salem.

The photograph is taken from a mass of old biotite-gneiss (No. 11,892) looking along the strike of the vertical foliation planes. The part of the hill shown is the east-north-east end of a large lens of garnetiferous norite (No. 11,895) whose long axis runs west-south-west. There are other lenses of the same rock further to the west; they have their long axes arranged in the same direction but not in line with this or with one another. A similar rock forms the summit ridge of Kanjamalai which can be seen in the distance on the left-hand side of the photograph. This hill and Kanjamalai are the ones referred to by Leschenault de la Tour in his "Relation d'un voyage à Karikal et à Salem" (*Mem. du Mus. d'Hist. Nat.*, vol. VI (1820), pp. 343, 344).

Plate XII.

View of Yercaud Lake and the Shevaroyen.

The photograph, taken from Arthur's Seat near Yercaud, looks northward across the lake to the highest point (5,300 ft.) on the Shevaroy plateau. The view is intended to give an idea of the scenery formed by the weathering, at an altitude of 4,000—5,000 feet, of a large uniform mass of the "intermediate" varieties of the charnockite series. The plateau of the Nilgiris which is at an elevation of about 7,000—8000 feet is not so well wooded, and consists of a series of undulating turf-covered "downs" with clumps of trees in the hollows.

Plate XIII.

Dyke of Charnockite series in Biotite Gneiss.

In the eastern part of Coorg the charnockite series, besides forming large masses, occur as dykes which are generally garnetiferous. They cut through biotite-gneiss approximately parallel to the foliation strike in a N.W.–S.E. direction, and are often themselves slightly foliated. The rocks which form these dykes are composed of the minerals which characterise the intermediate and basic members of the charnockite series, and are granulitic in structure though comparatively fine-grained. The selvages of the dykes are more compact, more basic and more hornblendic than their central portions.

T. H. Holland, Photo

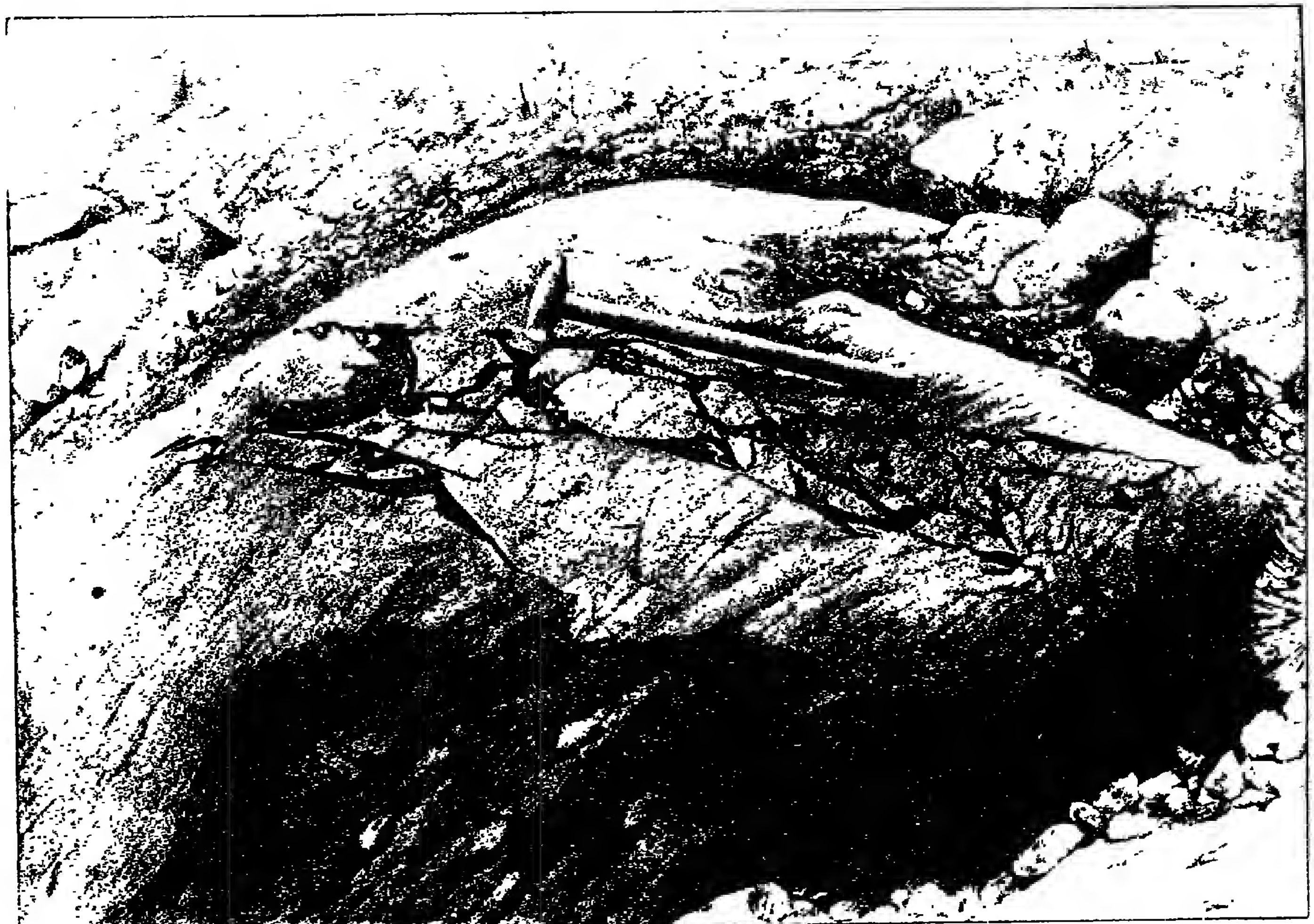
Photogravure, Survey of India Offices, Calcutta, January 1900

CHARNOCKITE DYKE IN BIOTITE GNEISS, FRASERPET, COORG

Plate XIV.

Dislocation breccia.

The peculiar phenomenon described on pp. 198—202 under the name "trap-shotten" gneiss was thought by older workers in South India to be due to the injection of compact basic material into the gneisses. But microscopic examination shows the black compact material to have the characters of mylonite, whilst the disposition of these so-called "trap-shotten" bands in the field shows them to coincide with lines of dislocation. The mylonite is extremely hard and brittle, and probably has been highly heated, though not fused, by the heat produced during the dislocation of the rocks; it has a composition similar to that of the rocks it occurs in, and has none of the characters of basic, compact, trap rocks.



From a Photograph by T. H. Holland. Lith. Geol. Survey of India Office.

SO-CALLED "TRAP-SHOTTEN" GNEISS.

South of Salem.